DEPARTMENT OF COMMERCE

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BUREAU OF STANDARDS

S. W. STRATTON, DIRECTOR

No. 58

STRENGTH AND OTHER PROPERTIES OF CONCRETES AS AFFECTED BY MATERIALS AND METHODS OF PREPARATION

BY

R. J. WIG, Engineer Physicist
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and
E. R. GATES, Assistant Physicist
Bureau of Standards

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By R. J. Wig, G. M. Williams, and E. R. Gates

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I. INTRODUCTION

Concrete differs from most structural materials in that it is not manufactured at a mill or plant according to chemical formulæ under the observation of skilled specialists and subject to rigid inspection, test, and such control as to produce a uniformly homogeneous product, nor is the process of manufacture completed in a few hours or days, as in the case of steel products. Furthermore, concrete is made from materials obtained from many sources differing widely in characteristics which affect its quality. The proportions of the ingredients, the amount of water used in mixing, the thoroughness of mixing, the manner of placing, the atmospheric temperature and humidity, exposure to sun, rain, and wind, immersion in fresh water, sea water, or other natural solutions, all affect the quality of the concrete.

The quality of structural steel can be determined easily and quickly at the place of manufacture and the strength of a fabricated structure is readily calculated. The physical qualities of the metal are unchanged during erection, provided good practice in design and construction have been followed, and the strength of the completed structure is directly dependent upon the strength of the steel as originally determined.

In most cases the inspection of the materials which are used to fabricate concrete is confined to tests of the cement, although the strength of a structure made of concrete can be no more completely determined by inspection of the cement than can the strength of structural steel be measured by an analysis of the iron ore from which the steel is to be made. Concrete made with cements of standard quality but with different aggregates may, in one case, have considerable strength and, in another, practically no strength. With the same cements and aggregates but with different workmanship in fabrication one concrete may have several hundred per cent greater strength than another. Concretes which are permitted to dry permanently from the time of mixing will never attain the strength of concretes of similar mixture which are supplied with water from time to time after mixing.

The principal requisites for a concrete aggregate are cleanliness, strength, homogeneity of structure, and proper gradation of particles. The relative values of these variables are difficult to determine and may not be the same in any two cases.

The coarse aggregates commonly used in concretes are granites, trap rocks, gravels, limestones, sandstones, slags, and coal cinders. These materials differ greatly in strength, hardness, porosity, and available gradation of size of particles. In any single type of material there can probably be found as great a range in quality as is commonly found between any two of the above types, excepting possibly cinders. It is generally considered that a granite is superior to a limestone as a concrete aggregate, but the range of quality among granites is so great that some limestones in use are superior to many granites. Specifications for concrete materials sometimes favor a limestone in preference to a gravel, due to the fact that gravel is usually round and smooth while crushed limestone is more angular and sharp, which are qualities that are supposed to aid in the production of a stronger concrete. Although this fact has not been demonstrated, there may be an interlocking of the particles of the angular material which would contribute to a greater strength of a green concrete. The effect of this, however, must be lost after the concrete is a few weeks old and the adhesion between the stone and cement is sufficient to prevent a breaking of the bond with stresses up to the shearing strength of the stone. The roundness of the gravel aggregate has certain advantages in flowing into place more readily and thus producing a denser mixture with less spading or tamping than is required for an angular aggregate.

Granite as a type of material may usually be superior to a limestone for use as a concrete aggregate, but in practice the exceptions are common enough to warrant comparative tests to determine the better, providing two or more types of material are available.

Safe design of concrete structures requires a knowledge of the compressive strength of the concrete within reasonable limits, since the working stress used in calculations is obtained by assuming a strength value and applying a factor of safety which should provide for all variations due to lack of uniformity in materials and workmanship and occasional excessive loading of the completed structure.

This factor of safety, however, can not be depended upon to care for the great variation in strength which may be obtained with various aggregates, even though workmanship and curing conditions may be of the best. Therefore, care must be exercised in selecting the aggregate if good quality of concrete is to be obtained.

In most communities, experience has demonstrated the satisfactory character of certain available aggregates and, therefore, no further tests are required except those which will detect variation in the quality, but untried materials should always be tested before using in important structures.

Many of the samples of sands which are included in this report were taken by representatives of the laboratory from localities where the Government was constructing public buildings or contemplated the construction of such buildings. The collectors (all geologists, with one exception) not only took the samples with particular care, but in addition secured information in regard to source, cleanliness, general appearance, etc. Unfortunately, the size of the sample was not as large in many cases as it should have been, so that not as thorough an investigation was made as might have been desired.

The large number of sands tested and the wide range of territory from which they were obtained, representing practically all kinds of sand found under the various geological conditions of formation, give the results of tests of sands obtained in this investigation more than usual interest. Furthermore, as standard Ottawa sand mortar specimens were made at the same time as the mortar specimens of most of the sands under investigation, a comparison of the strength of these sand mortars and the standard sand mortars, can be made with the assurance that they were subjected to the same conditions at all times.

The results included in this paper have been in part collated from the many investigations and tests made by the structural materials laboratories of the Geological Survey which were transferred to the Bureau of Standards in 1910, and from tests made by the Bureau of Standards.

The work in the Geological Survey was done by W. Jordan, jr., F. W. Cooper, William Linker, L. H. Losse, G. A. Riddle, R. Campbell, R. F. Havlik, A. D. Gates, and J. G. Bragg, under the direction of R. L. Humphrey. Acknowledgment is made to H. A. Davis and V. I. Richard for their assistance in making some of the tests in the Bureau of Standards. Some of the data were obtained as auxiliary tests to investigations reported in Geological Survey Bulletins 331 and 344, and Bureau of Standards Technologic Papers Nos. 2, 5, and 12. These data furnish information on the range of strength values which were obtained with different aggregates in various consistencies, with variation in workmanship of fabrication, in the method of placing, and in subsequent exposure. It contains results of tests on a relatively small number of aggregates and should not be considered in any sense an exhaustive study of the aggregates of the United States. A sufficient number have been included, however, to indicate that the ranges of values included herein are probably too low rather than too high, and an increase in the number of aggregates of any type studied would probably result in obtaining a wider range of values. The greatest value of this paper, perhaps, is in emphasizing the necessity of having a knowledge of all the materials used in fabricating concrete, and the necessity of exercising extreme care in every phase of the manufacture of concrete, if the good quality of the resulting concrete is to be assured and a concrete of known quality produced.

II. SCOPE OF TESTS

This paper includes the results of about 20 000 tests. Compressive and tensile tests were made upon mortars at different ages, including about 240 different sands and stone screenings and compressive tests were made on concretes composed of 60 aggregates, including limestones, gravels, granites, cinders, and trap rock, as well as tests of the physical properties of the sands, stone screenings, and coarse aggregates.

In order that the effect of each variable on the compressive strength might be determined, the consistency of the mixture,

the conditions of storage of the concrete, and the workmanship in fabrication were changed so that comparative results might be obtained.

The weight per cubic foot of the concrete, as determined from the weight of the test pieces, was recorded in all cases before making the compression tests, and compressometer readings were taken in most cases during the testing of the cylinders, from which the yield point and initial modulus of elasticity were determined. A series of comparative density and strength tests were made in a number of cases which show the effect on compressive strength of varying the relative proportions of the same fine and coarse aggregates.

III. TESTS OF CONSTITUENT MATERIALS

The cement used throughout most of these tests is known as a typical Portland cement and was prepared by mixing together a number of brands of standard American Portland cements. This cement was prepared by mixing in a concrete mixer, or by spreading on a large concrete floor an equal number of bags of cement of different brands in layers one above the other and turning with shovels until a uniform mixture was obtained. The cement was sealed in air-tight cans and stored away until used. It is assumed in this paper that all the cement used had the same cementing value. While this is probably an allowable assumption for the typical mixtures, it may not be so for individual brands, and therefore care should be exercised in comparing one group of results with another where different brands are used.

The aggregates as shown in Tables 1 and 1 *a* were for the most part secured from points in the Middle West, and in all cases were similar to the materials commonly used in concrete construction work in the particular localities from which the materials were obtained. The samples obtained varied in size from a few pounds to several carloads and were collected under the supervision of a representative of the laboratory or procured in the local market for use in the laboratory.

Tables 1 and 1 *a* contain the results of the granular analyses and other tests made upon the materials, such as specific gravity, weight per cubic foot, water absorption, and percentage of voids. A brief description of the methods used in securing the above results follows.

1. APPARENT SPECIFIC GRAVITY

COARSE MATERIAL (RETAINED ON ¼-INCH SCREEN).—A 1500 g (3.3 pound) sample, dried to constant weight, was placed in a tin bucket and the whole placed in a closed vessel and the air exhausted. Water was admitted, and after allowing the stone to soak for one-half hour the bucket was suspended on the arm of a balance and weighed while immersed in water. The result obtained by dividing the weight of the original dry stone by the loss of weight of the stone in water, corrected for absorption as described in the following paragraph, is called the apparent specific gravity.

The formula used in making this calculation is as follows:

$$S = \frac{W_d}{(W_d + A) - W}$$

in which

S = apparent specific gravity.
W_d = dry weight of stone in air.
W = weight of stone suspended in water.
A = total weight of water absorbed.

Two determinations were made on most samples, the values shown in Table 1 being the average.

FINE MATERIAL (PASSING THE ¼-INCH SCREEN).—The process was similar to the above except that a 50 to 150 g (0.11 to 0.33 pound) sample was used, and more care was taken in controlling the temperatures of the air and the water.

2. ABSORPTION

Small portions were selected so as to fairly represent the material from various parts of a large sample which had been previously spread out, and, after drying thoroughly and weighing, they were immersed in water. After attaining a constant weight, the material was surface dried, and a second weight was obtained from which the percentage of absorption was calculated. Check results were obtained from the samples used in the specific-gravity tests, since allowance had to be made for absorption before the specific gravity could be calculated.

3. WEIGHT PER CUBIC FOOT

The weight per cubic foot was determined by dividing the weight of dried material required to fill a given measure under a standardized condition of filling, by the volume of the measure. In making this determination a quantity of dried sand or stone was placed in an inverted conical vessel. The opening on the lower end was closed

by a readily removable slide and was 2 feet above the center of the measure ($\frac{1}{4}$ to 1 cubic foot). On removing the slide the material flowed quickly and evenly into the measure until it overflowed. The excess was carefully struck off without moving the measure. It was then weighed; the difference between the weight of the measure empty and the measure filled divided by the volume of the measure used gave the weight per cubic foot.

4. PERCENTAGE OF VOIDS

All results given in Table 1 are determined voids except where noted as "computed voids" obtained by calculation from the values obtained for specific gravity and weight per cubic foot.

The determined voids were obtained as follows: A graduated glass cylinder was partially filled with water, the level of which was noted, and a weight of sand corresponding to a given volume was slowly poured into the water. (The weight of the required volume of sand was calculated from the weight per cubic foot, which had been previously determined.) The sand was allowed to stand in the water for 30 minutes, when the water level was again taken. The method of computation follows:

A = volume of the sand (placed in measure under conditions specified under heading "Weight per cubic foot.")
B = volume of water = water level before sand was added
C = combined volume of sand and water = water level after the sand was added
V = per cent voids.

Then,

$$V = \frac{A + B - C}{A} \times 100$$

To correct for absorption, the product of the weight of the sand by the percentage of absorption was added to C.

Percentage of computed voids =

$$1 - \frac{\text{Weight per cubic foot dried}}{\text{Spec. grav.} \times \text{weight cu. ft. water}} \times 100$$

5. GRANULAR ANALYSIS

Two sets of screens were used for this test—one for material larger than $\frac{1}{4}$ inch and one for smaller material. The set of large mesh screens (openings $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$, 1, $1\frac{1}{4}$, $1\frac{1}{2}$, $1\frac{3}{4}$, and 2

inches) were 2 feet wide by 4 feet long and 6 inches deep, and they were suspended from the ceiling by ropes connected at the four corners.

A 100-pound sample, after drying, was placed on the ¼-inch screen, which was agitated by jarring against the wall until no material passed through, and the material which passed was saved. The portion remaining was then placed on the screen next larger in size, the sifting was continued in the same manner, and the sample was thus passed through the screens of all sizes.

The smaller-mesh sieves used for sand and stone screening analyses were the regular 8-inch diameter circular hand sieves with openings of 6, 10, 20, 30, 40, 50, 80, 100, and 200 per linear inch.

In order to obtain a sample for making the analyses of sands and stone screenings the entire sample, after mixing well, was spread out in a thin layer and divided into small squares, a total of 500 g. being taken. The remainder was remixed and resampled twice, obtaining in this way three 500 g. samples. Each sample was then sieved through the nest of sieves. The results given are the average of three determinations. These results were also used to determine the "uniformity coefficient" as defined by Hazen,[1] which is the ratio of the assumed diameter of the particles corresponding to the 60 per cent ordinate of the granularometric analysis curve, to the assumed diameter of the particles corresponding to the 10 per cent ordinate of the curve.

In proportioning the aggregates to produce the various concretes included in the series of cylinder and cube tests of Tables 8 to 15, the coarse aggregate was used as received, however large a percentage of fine material was contained in it, and the sand or fine aggregate was added in the proportion stated. In some cases, the fine material passing the ¼-inch screen which had previously been removed from the "pit or crusher run material" was later used as a fine aggregate with the "pit or crusher run material" as received. In Table 1*a* the values given for specific gravity, weight per cubic foot, and per cent of voids, preceding the granular analysis of the coarse material, are those corresponding to the material as received, unless otherwise noted, while the second set of above values refers to that part of the crusher or pit run material which passed the ¼-inch screen.

[1] Twenty-fourth Annual Report of State Board of Health of Massachusetts for 1892.

6. DENSITY

Values given for "density" of mortars were calculated from the formula:

$$D=\frac{1W_s\times R}{VS_s\times K}+\frac{W_c\times R}{S_c\times K}$$

The following formula was used to determine the density of concrete·

$$D=\frac{1W_s\times R}{VS_s\times K}+\frac{W_c\times R}{S_c\times K}+\frac{W_a\times R}{S_a\times K}$$

in which

D = Density.
W_s = Weight of sand or fine aggregate used
S_s = Apparent specific gravity of the sand or fine aggregate.
$R=\frac{W_m}{W_t}=\frac{\text{Weight of mortar in the mold}}{\text{Total weight of material used}}$
K = Unity when using grams and cubic centimeters, and 62.5 when using pounds and cubic feet.
W_c = Weight of cement used.
S_c = Specific gravity of cement.
V = Volume of the mold.
W_a = Weight of coarse aggregate used.
S_a = Apparent specific gravity of coarse aggregate.

The above is not the true density in that the water content of the mixture is not included as solid matter and the apparent specific gravity, rather than the true specific gravity, of the fine and coarse aggregates are used in the calculation. With these exceptions the term "density" is used to represent the ratio of the volume of solids to the volume of the mold.

The term "density" is used throughout this paper in the above sense and should not be confused with specific gravity.

The determination was made as follows: The quantity of cement, sand, and coarse aggregate for a given volume was measured by weight calculated from their previously determined weights per cubic foot. The quantity of water required to obtain the desired consistency was also weighed. Part of the mixed mortar or concrete was tamped into the mold, the weight and volume of which had been previously determined, the excess was struck off with a straightedge, and the filled mold weighed. The net weight of each ingredient in the total mixture, multiplied

by the ratio of the weight of the mortar or concrete in the mold to the total weight of all the materials weighed out and mixed, gave the net weight of the cement and aggregate contained in the mold. It was assumed that the mixture was uniform, and no allowance was made for the evaporation of water which might occur during the time required for mixing and weighing. With the above values the "density" was determined from the formula as given.

IV. DETAILS OF TESTS OF MORTARS AND CONCRETES

1. METHODS OF MIXING AND MOLDING

The large test pieces used were made up principally of 6-inch cubes and cylinders 8 inches in diameter and 16 inches long. The cube and cylinder molds were made of cast iron in sections with the inner surfaces machined and the sections fastened together with brass clamp screws. For the density tests, which are described later, molds of wrought-iron pipe capped at one end were used.

Compression and tension specimens were made from most samples of sand and stone screenings. Three-gang standard briquette molds were used for molding tension specimens and three-gang 2-inch cube molds for most compression specimens. Some compression tests of mortars were made on 6-inch cubes and 8 by 16 inch cylinders. Standard practice [2] for the molding of briquettes was followed in the preparation of these small specimens.

There were made at frequent intervals 1:3 standard Ottawa sand specimens for comparison with the sands under test.

For proportioning the various mixtures the weight of a cubic foot of cement was assumed to be 100 pounds, and the proportions indicated throughout this paper and in the tables of results are by volume measure. The figures 1:2:4, 1:3:6, etc., signify the ratio of cement to fine aggregate to coarse aggregate by volume. For convenience and greater uniformity in proportioning the volume measurements were transposed to weight measurements. More uniform proportions can be obtained in this manner, since the weight of a given volume of sand varies greatly with the moisture content and with the method of filling the measure; unless this variation is cared for the actual proportions of the mixture will not be constant.

[2] Bureau of Standards Circular No. 33, United States Government Specification for Portland Cement.

After the desired proportions were determined the weight of dry material for each batch was calculated. The moisture content of the sand and coarse aggregate to be used was determined and the calculated dry weights of each were increased by an amount equal to the amount of moisture present.

This percentage of moisture was determined on 500 g. samples of the aggregate to be used during that day. An allowance for the amount of moisture so found is then made in weighing out the water, the total amount of which for the correct consistency was predetermined. It is usually found, even after making this moisture correction, that the consistencies of the various batches will vary enough to be easily apparent, both to the eye and in the process of molding. This is due to the fact that the amount of moisture in the sand varies considerably and the correction determined by drying a small sample does not fairly represent the amount present throughout the mass. The total amounts of water used for each proportion were recorded and an attempt was made to make the consistencies of batches of the same proportion uniform.

The consistencies referred to throughout this paper from the driest to the wettest may be defined as follows:

Dry.—Containing just sufficient water to cause the cement and sand to adhere after tamping and removal of the molds.

Moist.—A mean between the "dry" and "plastic" consistencies.

Plastic.—Containing the maximum quantity of water which allows the removal of the forms immediately after molding. The surface of the mass shows weblike marks of neat cement and water.

Quaking.—A stiff mixture upon which water can be brought to the surface by slight tamping. The mass should not flow readily.

Mushy.—A soft mushy mixture which is not watery, but can be spaded and readily worked into place in the form.

Fluid.—A watery mixture which flows readily into place in the form with little or no working.

A photograph of three batches of concrete to illustrate the three consistencies, "quaking," "mushy," and "fluid," are shown in Fig. 1. In forming each of the piles the concrete was allowed to slide from the shovel and drop only a few inches onto the pile, the weight causing the material to spread out and take the shapes shown. Dumping from a barrow or allowing the mixtures to flow from a chute would have caused the materials to spread further and form flatter cones, which would give the appearance of wetter consistencies than the method which was used.

The difference in appearance of the dry, moist, and plastic mortars is not sufficient to be illustrated by photograph, and can best be determined and measured by squeezing a mass in the hand.

All concrete was mixed in power-driven batch mixers, unless indicated differently in the tables of the results. Water was weighed and supplied to the mixer through a hose attached to a barrel, which was mounted on a platform scale above the mixer. To insure uniform conditions the interior of the mixer was wetted down each morning before the first mix was made. Concrete was usually mixed about two minutes dry and three minutes wet, or until an apparently homogeneous mixture was obtained, excepting where otherwise noted.

The quantity of water used in mixing and the consistency of the mixtures is given with the results of tests in the tables.

The test pieces were for the most part prepared by filling the mold about one-quarter of the height at a time and tamping with a hand tamper, care being exercised to lift the tamper the same height each time and to move it systematically over the entire surface at each partial filling. The top surface was finished by troweling with a plasterer's trowel.

Since it was desired in one series of tests to determine the effect on the compressive strength of depositing concrete below the surface of water, it was necessary to employ a different method of molding. When the test pieces were to be molded in submerged molds the concrete was placed through a tremie or pipe. The pipe was 30 inches in length and 5 inches in diameter. A cloth was placed over the bottom of the pipe, the pipe was filled with concrete to a depth of 25 inches, and was then immersed until the bottom of the pipe rested on the bottom of the mold, when the cloth was withdrawn from the bottom of the pipe. The pipe was then gently raised from the bottom a little at a time, the concrete flowing from the pipe, which was continually supplied with concrete so that the level of the concrete in the pipe was always above the level of the water. This was continued until the mold was full, when the concrete was allowed to overflow slightly and the top was somewhat leveled with a plasterer's trowel.

2. STORAGE

The molds, unless otherwise noted, were stripped from all specimens 24 hours after molding and the large cubes and cylinders were stored in a moist room where they were sprinkled three times daily, while the 2-inch cubes and briquettes were stored in water. The temperature of the molding room, the moist room, and water in storage tanks were maintained as near 70° F. as possible.

3. METHODS OF TESTING

Just previous to testing the cylinders were removed from the place of storage, weighed, and measured. To insure uniform bearing in the testing machine and the application of the load parallel to the vertical axis of the cylinder, the ends were "capped" in the following manner with thin layers of plaster of Paris or plaster and cement:

A small amount of plastic mixture was spread on a horizontal glass-topped table and the end of the cylinder, which had previously been wet, was forced down into the mass until the material flowed out to the edge, and at the same time the axis of the cylinder was made vertical by applying a spirit level to the sides of the cylinder. The mixture hardened in a few minutes and the cylinder was rotated about the vertical axis and carefully slipped horizontally from the plate. The other end of the cylinder was prepared in the same manner. The cap was prevented from sticking to the plate by covering the plate with a thick film of oil just previous to placing the mixture of plaster and cement. The relative quantity of plaster and cement needed varies with the condition of the plaster. Too much cement causes the cap to harden slowly and increases the danger of partially destroying the cap in slipping the cylinder from the plate. In forming the cap on the opposite end of a cylinder the cap first formed is tested by applying the level to the top after the sides have been made vertical. Usually the cylinders were not tested until several hours after "capping."

In testing, a cylinder was centered on a spherical bearing block and placed on the weighing table so that the vertical axis of the cylinder was in a line passing through the center of the movable head. To insure full bearing at the top, the cylinder and upper section of the spherical block were slowly rotated horizontally by the operator while the upper head was brought down onto the test piece and the load was applied by a uniform movement of the head of about 0.02 inch per minute.

In most cases a compressometer was used to obtain stress strain readings nearly to the point of failure. These readings were then plotted and the modulus of elasticity and the yield point determined.

The cubes were not capped with the plaster mixture before testing, but were merely placed in the machine on the spherical bearing block with pieces of asbestos or blotting paper just above

and below the bearing surfaces of the cube. The head of the machine was brought down to uniform bearing in the same manner as for the cylinders. No deformation readings were taken on the cubes.

V. RESULTS OF TESTS

Practically all of the results given in this paper are the averages of three or more tests. The results are given in tabular form and some diagrams have been prepared to show the comparative strength of mortars and concretes with various aggregates and for various proportions and mixtures. Since the laboratory conditions were especially favorable for the uniform hardening of concrete, the results obtained in the laboratory are probably higher than those which would be secured from the same materials under normal field conditions.

1. PORTLAND CEMENT MORTAR MIXTURES

(A) Compressive Strength of Cubes and Cylinders.—The average compressive strengths of mortars of several proportions and consistencies and at various ages are given in Tables 2 to 5. The results given in Tables 2 and 3 were obtained from tests of 8 by 16 inch cylinders and those of Tables 4 and 5 from tests of 2-inch cubes. Tests were made of mixtures of three consistencies—dry, moist, and plastic—which were similar to those used in the manufacture of building blocks by the "dry" process. The "plastic" consistency, which was the wettest of the series, had the greatest strength at all ages and in all mixtures excepting the 1:8 mixture, in which there is practically no difference in strength between the "moist" and "plastic" consistencies.

As stated on page 14, the plastic consistency does not contain as much water as the quaking or mushy consistencies most commonly used for concrete. No tests were made of fluid or very wet mortar mixtures, and therefore their effect on strength is not known, although it is probable that the fluid consistency mixture would have less strength than the plastic consistency mixture, as is the case with concrete. The strength varies with the relative proportions of cement and fine aggregate, the 1:2 mixture being strongest and the 1:8 weakest, but all proportions show increased strength with age. The relative strength of these mixtures are shown diagrammatically in Fig. 1*a*.

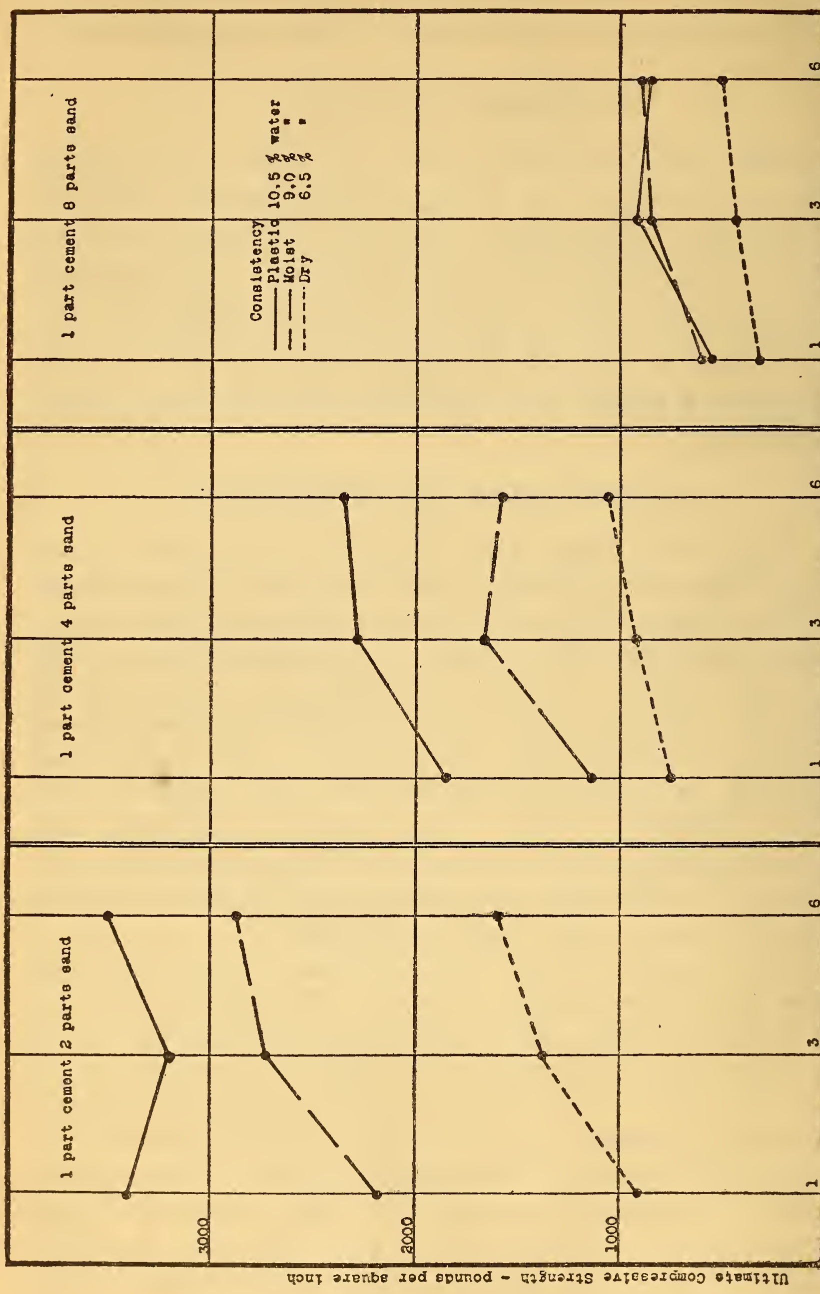

FIG. 1a.—*Relation of consistency of various mixtures of Portland cement sand mortars to compressive strength at various ages. (Test pieces, 8 by 16 inch cylinders. See Table 2 for complete data)*

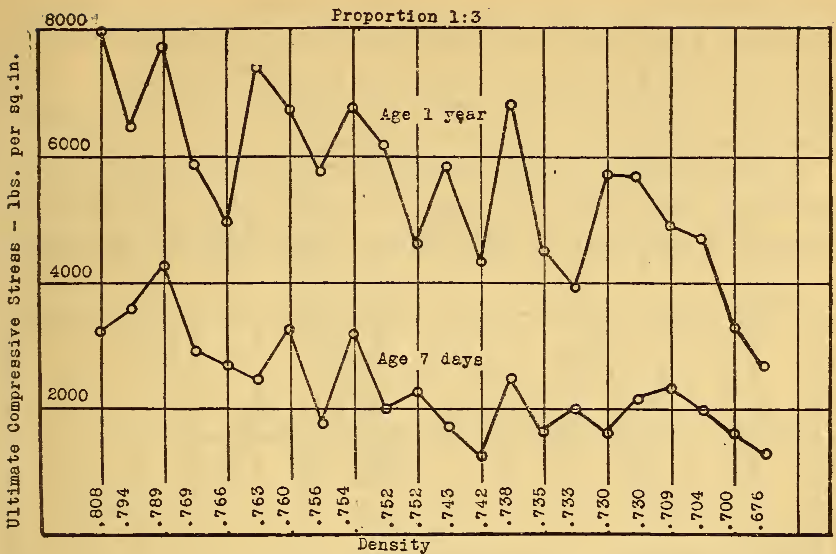

FIG. 2.—*Relation of the density of 1–3 mixtures of Portland cement sand mortars made with different sands to the compressive strength at the ages of 7 days and 1 year. (Test pieces, 2-inch cubes. See Table 4)*

FIG. 3.—*Relation of density of 1–3 mixtures of Portland cement gravel screening mortars made with different materials to the compressive strength in both 1–3 and 1–4 mixtures at the ages of 7 days and 1 year. (Test pieces, 2-inch cubes. See Table 4)*

A comparison of the results of tests of sand 186 and limestone screenings show that these particular limestone screenings make a much stronger mortar at all ages than the sand aggregate. More water was required by the screenings, probably due to its greater fineness and porosity of grain as compared to that of the sand.

The results given in Table 2 would indicate that variation in the amount of water used in a mortar will cause as large differences in strength of the mortar as will the use of two dissimilar aggregates

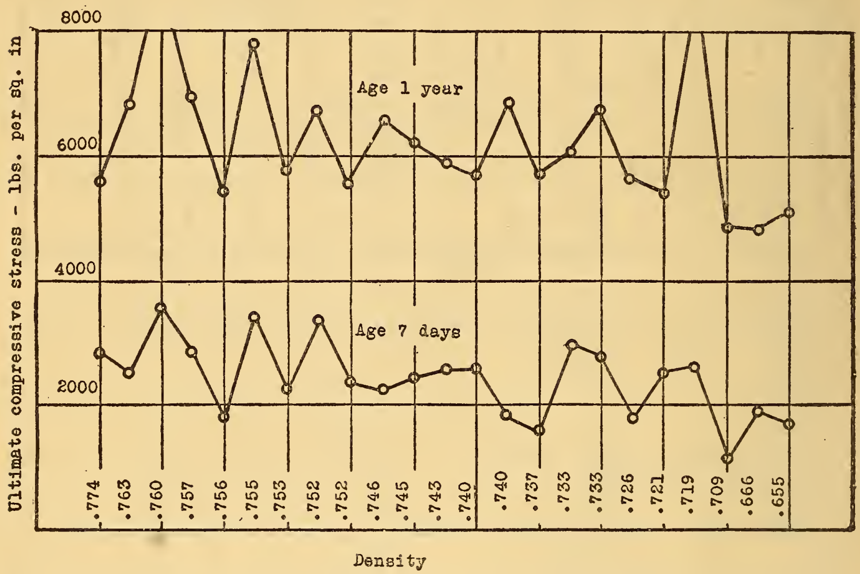

FIG. 4.—*Relation of the density of 1–3 mixtures of Portland cement stone screenings mortars made with different materials to the compressive strength at the ages of 7 days and 1 year. (Test pieces, 2-inch cubes. See Table 4)*

with the same cement or a reduction of 50 per cent in the quantity of cement used.

In Table 3 are shown the results of additional tests on mortar cylinders made up in the proportions of 1 : 1, 1 : 2, and 1 : 4, and tested at 4 and 13 weeks. The two richest mixtures attain high values at both periods. The yield points and moduli of elasticity are proportionately high. Since the same sand was used in the concrete tests reported in Tables 8 to 15, these results may be compared. It is also of interest to note that the results obtained on the large cylinders compare favorably with those obtained on the 2-inch cubes reported in Table 4.

Tables 4 and 5 give the results of tests on mortars made up of typical cement and a large number of aggregates which are in

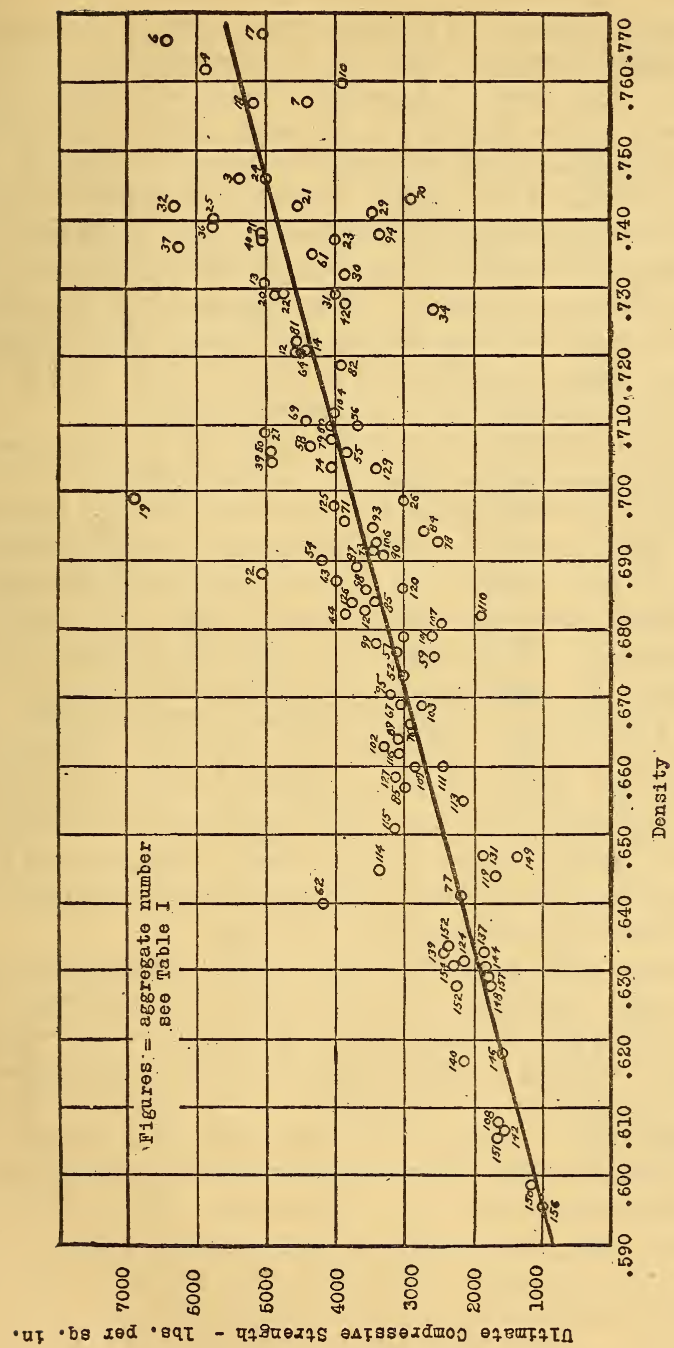

FIG. 5.—*Relation of "density" or solidity ratio to compressive strength of mortars. Proportions, 1 part Portland cement to 3 parts sand. Age, 13 weeks. (See Table 5.) (The numbers on the diagram correspond with the sample numbers of Table 1, No. 1 being the coarsest sand and No. 157 the finest)*

common use in concrete throughout the United States. The results given in Table 4 are arranged in the order of the density of the resulting mortars as made up in the proportion of 1 part cement to 3 parts sand or screenings. Since an endeavor was made to mix all the materials to the same plastic consistency, a direct comparison of the compressive strength is afforded, as all other conditions were uniform. Some of the results of these tests are shown diagrammatically in Figs. 2, 3, and 4, in which the strength results are plotted in the order of their densities for two ages, seven days and one year. These diagrams show that there is no direct relation between density and strength when comparing different aggregates, although as a group those having the greater density generally have the greater strength.

The results in Table 5 are arranged according to fineness, sand No. 3 being the coarsest and sand No. 157 the finest.

The ratio of the compressive strengths of the mortars made of the sands tested to the compressive strengths of the mortars made from the standard Ottawa sand is much higher than the tensile ratio in the case of the coarse sands; the finer sands show that this ratio is reversed, and the sands of intermediate fineness give approximately the same ratios in compression and tension.

In Fig. 5 compressive strength is plotted against density. It is quite evident that the strength of a mortar follows the density more closely than any of the other properties of the sand, though a high density may in some cases be accompanied by low strength.

In general, there is a very good increase in strength with age, although in a few cases there are marked decreases at the one-year period, for which no explanation can be offered.

In the results of the sand mortar tests, Table 4, it should be noted that the sands containing a comparatively low percentage of material passing the No. 50 sieve have high compressive strengths, while those containing a higher percentage of fine particles usually have a comparatively low strength. In the gravel screening mortar tests the 1:3 mortar made with sand 309 is exceeded in strength by that of sand 302, which attains the maximum strength of all the aggregates represented in these series. However, in the 1:4 mortar, sand 309 is nearly 50 per cent the stronger. The analyses of the materials in Table 1 show that sand 309 contained an unusually small amount of fine material, only 0.7 per cent passing the No. 10 sieve, while sand 302 contains next to the greatest amount of fine material of all the gravel screenings; but sand

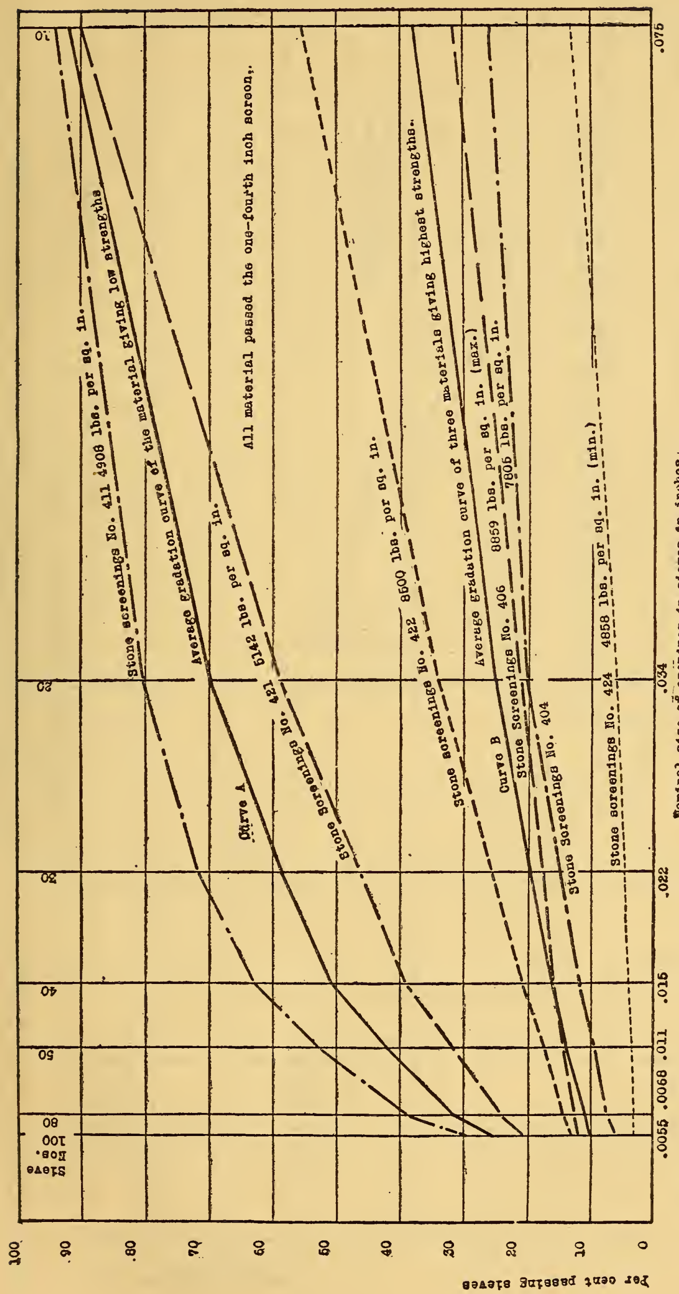

FIG. 6.—Granular analyses of stone screenings, showing relation of the gradation of particles to the compressive strength of 1–3 mortars. Age, 1 year. (See Tables 1 and 4 for complete results)

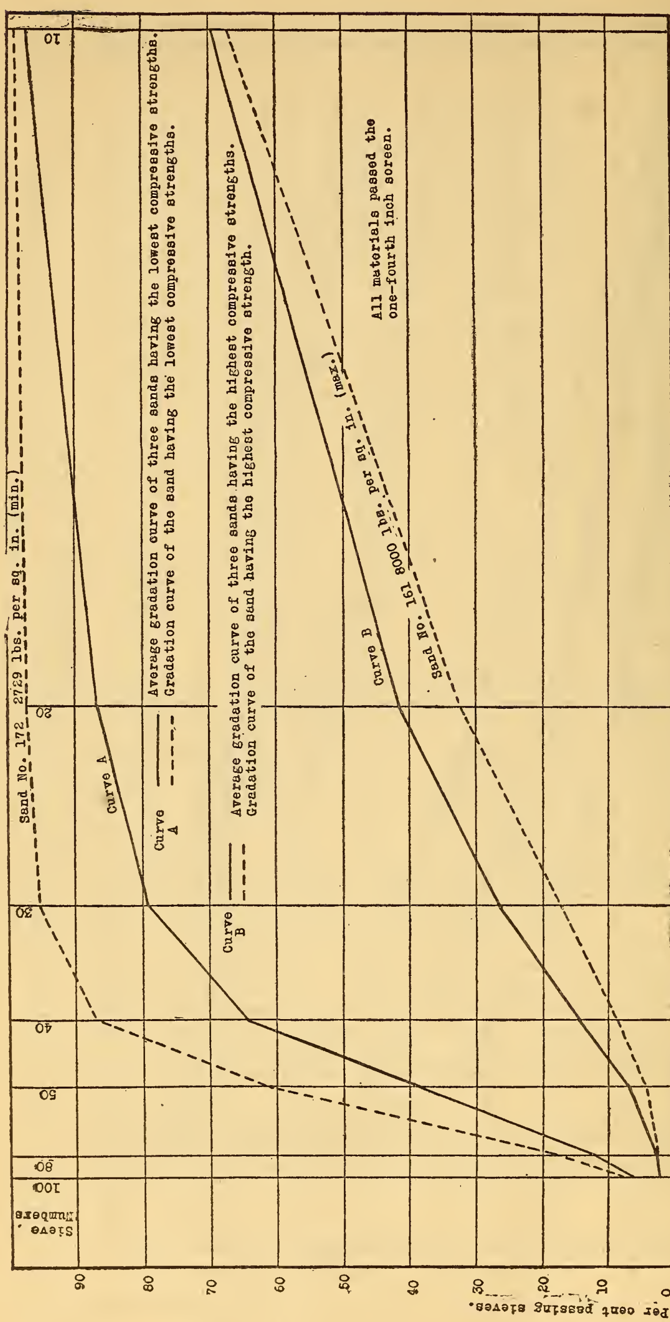

FIG. 7.—*Granular analyses of sands, showing relation of the gradation of particles to the compressive strength of 1–3 mortars. Age, 1 year.*
(See Tables 1 and 4 for complete results)

306, which contains the largest amount of fine material, is nearly 300 per cent stronger in both proportions than sand 308, which has nearly as little material passing the No. 10 sieve as sand 309.

In the sand mortar tests the strength of the mortar made of sand 162 shows a marked reduction at the year period over that of the six-month period in both the 1 : 3 and 1 : 4 proportions. A number of the other sands show either slight reductions or only small increases in strength between the six-month and one-year periods. In the results of the tests of the stone screenings the long-time tests appear to be uniformly high with a few exceptions. Screenings 410, 407, 415, 411, and 424 were unusually low in strength in the 1 : 4 mixture at the seven-day period, but with the exception of 415 and 424 show good increases in strength at each test period up to one year.

In order that the effect of gradation of particles on the compressive strength of mortar may be more easily seen, Figs. 6 and 7 have been prepared. Curve *B*, Fig. 6, represents the granular analyses of an aggregate whose particles are the average of the three-stone screenings 404, 406, and 422, which gave the highest compressive strength at one year. Stone screenings 424, which is the coarsest of all those tested, at the year period attained the lowest strength. Curve *A* is plotted by averaging the curves for stone screenings 411 and 421, which gave the lowest results, excluding those of 424.

In Fig. 7 the highest and lowest testing sands of Table 2 are shown in the same manner. Curve *B* represents the average size of the grains of the three sands which attained the highest compressive strength at one year, while curve *A* represents the average size of the three having the lowest compressive strength. The curves for the sands having the maximum and minimum strengths fall respectively below and above these average curves.

The above two diagrams show very clearly that a relatively coarse rather than a fine sand is likely to be most satisfactory in use. In general, the straight-line gradation may be said to be the ideal gradation, but the curve of stone screenings 424, Fig. 6, indicates that the proportion passing the coarser sieves should not be too low. However, such a material is rarely used as a sand, and in most cases sands are too fine rather than too coarse.

No definite conclusion regarding the effect of gradation of particles on the compressive strength of the mortar can be drawn from these results. They show in a general way, however, that sands

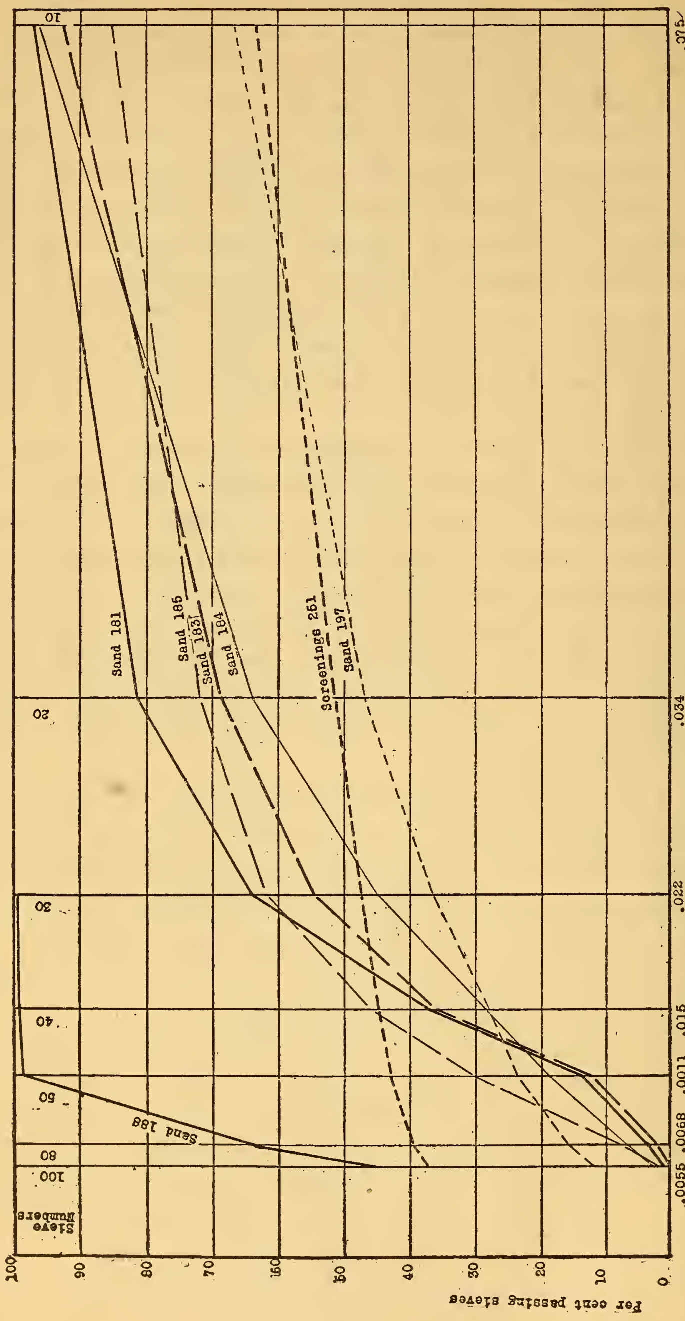

FIG. 8.—*Granular analyses of some of the sands and stone screenings used in tests, showing the wide variation in gradation. (See Table 1)*

whose gradation approaches a straight line and have preferably not in excess of 30 per cent passing the No. 50 sieve (normal opening 0.011 inch) give the greater compressive strength in mortars. There are sands which have a larger amount of fine material which give good results in mortars and concretes, therefore it should not be assumed that the strength is entirely a function of the gradation of the fine aggregate. The specifications of the American Concrete Institute[3] for fine aggregates would reject 85 of the 197 sands included in Table 1, or 43 per cent, on account of excess fineness, and many of these will be found to give good results, as shown in Tables 4 and 5. It will also reject several of the sands shown in Fig. 8, which appear to be satisfactory when used in concrete.

It should, furthermore, be recognized that the sand which gives the highest compressive strength in a mortar will not necessarily give the greatest strength as compared with other sands combined with a given coarse aggregate in a concrete, due to the fact that there are often small quantities of material included in the coarse aggregate which passes the ¼-inch screen or a large percentage of both the fine and coarse aggregate is near the ¼-inch size, and its effect on the strength of the concrete is the same as though this excess amount were present in the sand, thereby materially altering the gradation of the combination. In Fig. 8 sand 188 would probably be rejected for use as a concrete aggregate by visual inspection, but it should be noted, as shown in Table 16, that the concrete in which this sand was used attained a strength of over 2000 pounds per square inch at four weeks.

Although no definite conclusion can be drawn in regard to the proportions of fine material required for maximum strength, in the majority of cases, those mortars containing the higher per cent of fine particles show the lower compressive strengths.

From the results shown in Table 4 it is not possible to say that any one of the three types of aggregates represented is superior to the others for use in a mortar. The range of values obtained with any one type is so much greater than the range of the average of all three types that it is very evident that the source or type of material is of minor importance.

(B) Compressive Strength of Building Blocks.—In Table 6 are given the average results of tests of cement mortar building blocks.

The materials used were sand 183 with a "typical" Portland cement mixed in the proportions 1:2, 1:4, and 1:8, each propor-

[3] Journal American Concrete Institute, October, 1914, p. 17.

tion including the three consistencies "dry," "moist," and "plastic." The per cent of water used was as follows:

Consistency	Proportions (cement:sand)		
	1:2	1:4	1:8
	Per cent water used		
Dry	6.5	5.5	4.5
Moist	9.0	8.0	6.5
Plastic	10.5	9.0	8.0

The blocks representing each of the above proportions and consistencies were made on five commercial block machines which were in common use at the time the tests were made.

The blocks which are shown in Fig. 9 may be described briefly as follows:

Machine A: Two-piece wall block with web at center.

Machine B: One-piece double air space 4-core block.

Machine C: One-piece single air space single-core block.

Machine D: One-piece single air space 4-core block.

Machine E: One-piece single air space double-core block.

Owing to the fact that a single block would, in compression, exceed the capacity of the largest available testing machine, the transverse tests were first made and then portions of the two halves were tested in compression. A parallel set of mortar cylinders were molded at the time the blocks were made and tested at later periods for compressive strength.

The transverse strength was determined on a 20-inch span with the load applied at the center of the block.

All blocks and cylinders were tamped to weigh within ¾ pound of a prescribed weight to insure uniform density as a whole, but since all specimens were hand tamped there was no assurance that the different portions of the mass were homogeneous. It is probable, however, that these specimens compared favorably with the commercial hand-tamped block.

The modulus of rupture was figured for each type of block at a transverse plane, where rupture usually occurred, and this gave the maximum value. For blocks C and D this section was the center, while for the others it was about 2 inches from the center, or where the web joins the wall of the block.

Since the broken portions of the blocks were used in the compression tests the pieces tested for compression were not uniform,

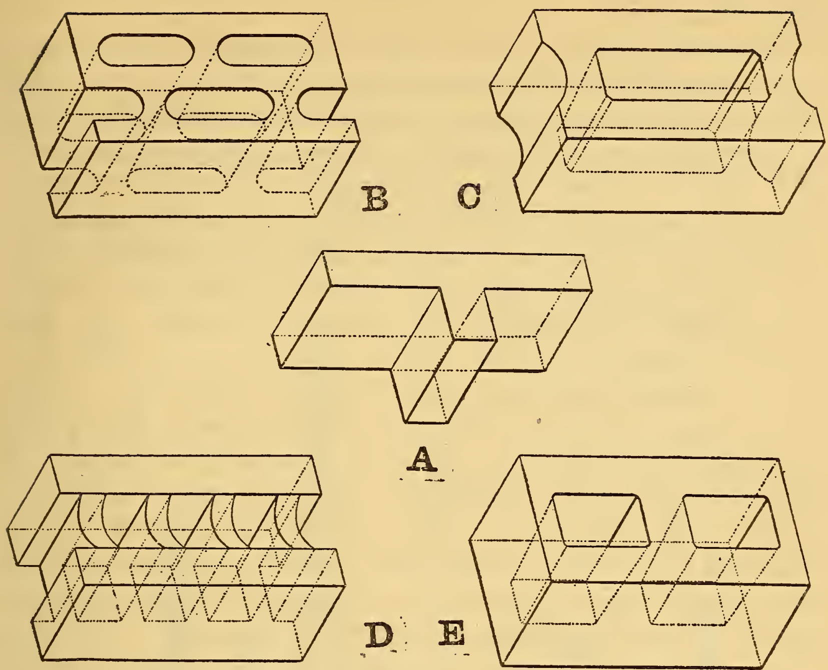

FIG. 9.—*Types of mortar building blocks used in tests*

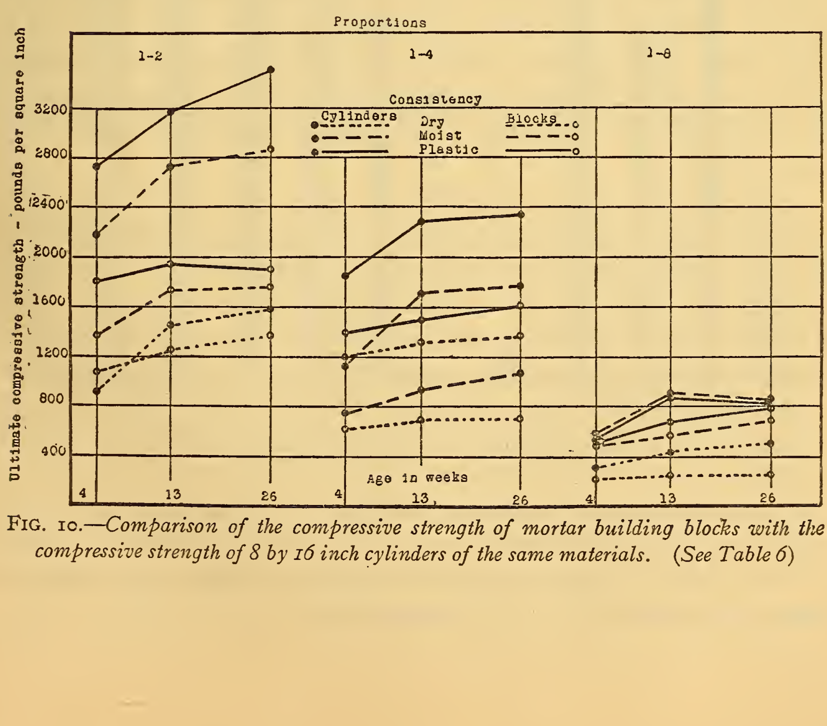

FIG. 10.—*Comparison of the compressive strength of mortar building blocks with the compressive strength of 8 by 16 inch cylinders of the same materials. (See Table 6)*

and the smallest area of the piece was used in calculating the unit stress.

The results given in Table 6 show that with few exceptions the mortars mixed with the greatest amount of water were strongest. There is not a close agreement between the compressive strengths as determined from the cylinders and from portions of the blocks. (See Fig. 10.) These differences may be accounted for in four ways, (*a*) shape of test specimen, making the method of calculation incorrect, (*b*) previous injury to sections of the block during the transverse test, (*c*) improper centering of the block in testing machine, and (*d*) difference in methods of molding and curing cylinders and blocks.

The cylinders would be expected to have a lower unit strength than the pieces of blocks if the variation was due in large part to the method of calculation on account of the irregular shape of the block test piece. The cylinders, however, in most cases, had a greater unit strength than the block sections. It is possible that some of the block sections were injured during the transverse test in such a way as to affect the compressive strength, but there was no way of determining the extent of this injury. The block sections being of odd shape, it was often difficult to center them in the testing machine and the load was applied eccentrically, which would result in failure at a load under that which might occur if uniformly loaded. The blocks were molded with special tampers, and the thin walls would probably be more difficult to tamp than the cylinders; also the blocks were removed from the molds immediately after molding while the cylinders remained in the molds for 24 hours, which may account for some of the variations.

While these results may indicate that some of the machines may turn out blocks superior to the others as to strength, as shown in Fig. 11, it should be considered that within practical and ordinary commercial limits the strength of the individual blocks is usually a secondary consideration and that the real value of the building block is measured by its moisture proof or water repellant qualities. These qualities are more dependent upon selection, proportioning of materials, and processes of manufacture than upon the type of machine used. The automatic tamper, which is now in general use, aids in securing a dense, homogeneous block, and allows the use of a slightly wetter mortar than can be molded by hand. Where the blocks are covered with stucco their water repellant properties are not of so much importance.

(C) TENSILE STRENGTH OF BRIQUETTES.—Since sands have been commonly tested by determining their tensile strength in mortars as compared with standard Ottawa sand mortars, such tests were made of most of the sands and results are given in Table 7. The results of tests of sands 1 to 157 are arranged according to their

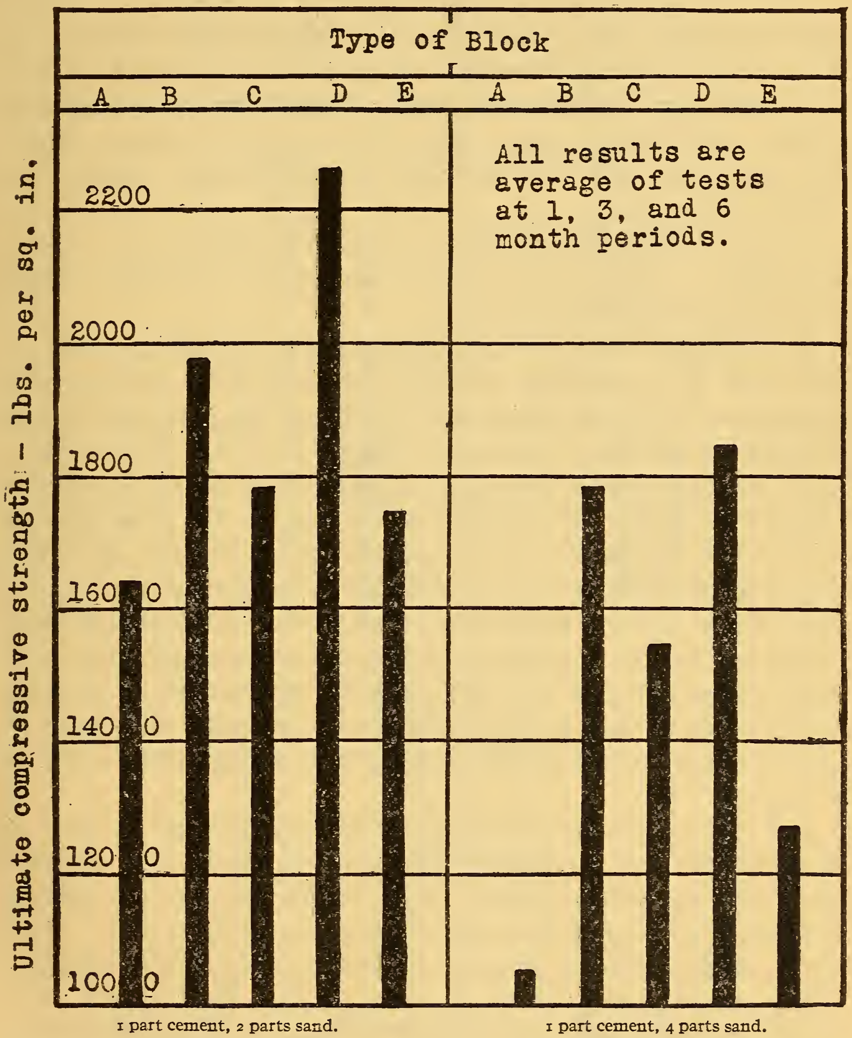

FIG. 11.—*Compressive strength of five types of mortar building blocks. All were made of a plastic consistency.* (*See Table 6*)

fineness, as indicated by the granularmetric curves, the coarsest being No. 1 and the finest No. 157. Results of tests of other samples are arranged according to density of the mortar.

The specification of the American Concrete Institute would reject 107 of 138 sands, or 78 per cent, on account of low tensile

strength as compared with standard Ottawa sand mortars. About 65 per cent of the samples had a tensile strength greater than 90 per cent of the strength of standard sand mortars. Many of these sands have a comparatively high compressive strength and would pass specifications if the latter required only compressive strength.

Fig. 12, in which the tensile strength at 13 weeks was plotted against density, shows some very large differences in strength for different sands when the density is approximately the same. There is practically no difference in tensile strength between the sands having rounded and sharp grains. The grand average tensile strength of all results is as follows: Rounded, 349; sharp, 342; medium sharp, 341.

In Fig. 13 the tensile results have been divided into four groups, according to strength, and plotted according to Feret's [4] three-coordinate method for such tests.

In this figure the *F* or fine particles are those passing a No. 30 sieve, the *M* or medium particles those passing a No. 10, but retained on a No. 30 sieve, and the *G* or large particles those retained on the No. 10 sieve, but passing a ¼-inch sieve. These were the only sieves available nearest those originally recommended by Feret. The proportion of each of the three sizes in the sand is represented by its perpendicular distance from the side opposite each apex. For example, at the apex *F* the composition is $F=1$, $G=0$, and $M=0$. This method indicates but very little more clearly the relation of fineness and strengths than the customary plotting of the entire granularmetric analysis. It does, however, show that generally the lower strengths are obtained from the finer sands. In Fig. 14 is shown typical gradations of fine and coarse sands.

In Table 7*a* are shown the results of long-time tensile tests of neat cements and of standard Ottawa and quartz sand mortars made with the same cements. With the exception of the cement from bin 5, all cement used was produced by the same mill. With few exceptions the neat cements attained their maximum strength at the ages of 26 or 39 weeks, the strength then decreasing until at 5 years it was approximately equal to that at the age of 3 days. The 5-year average for the neat tests is just high enough to pass the present 28-day specification requirement of 600 pounds. The mortar briquettes reached their maximum strength between the ages of 13 weeks and 1 year, and after that period show a falling

[4] Annales des Ponts et Chaussees, 1892, "Concrete, Plain and Reinforced," by Taylor and Thompson, p. 144.

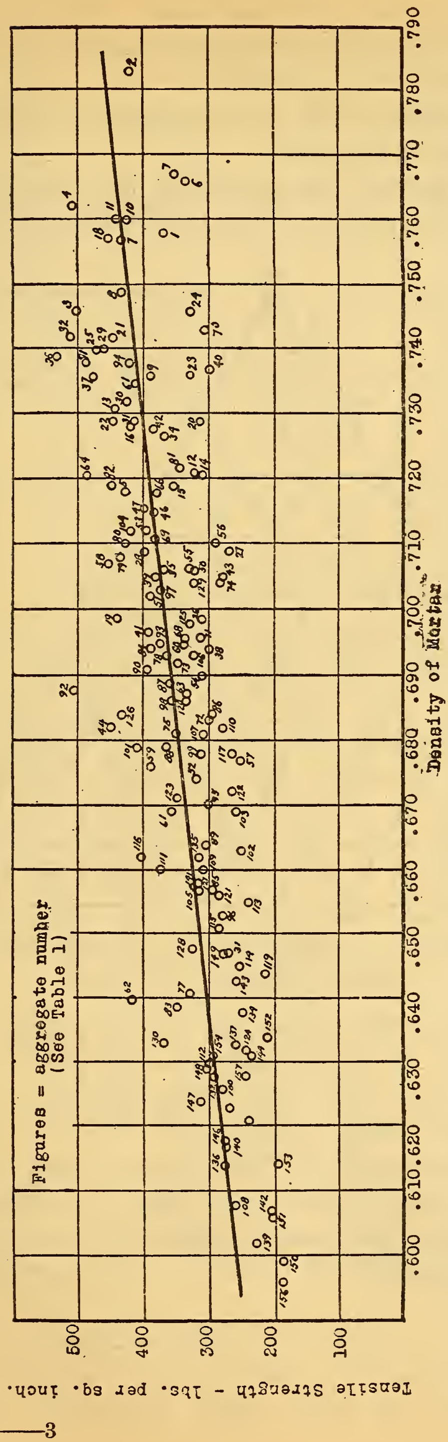

FIG. 12.—*Relation of "density" or solidity ratio of mortar to tensile strength. Age, 13 weeks. Proportions, 1 part cement to 3 parts sand. (See Table 7)*

17153°—16——3

off of about 30 per cent of the maximum. The Ottawa sand mortars are at all later periods generally well above the 28-day specification requirement of 275 pounds.

The grand average results of all samples at each age are shown diagrammatically in Fig. 14*a*.

The specific gravity and percentage of absorption of sands seem to bear little relation to the tensile strength of the mortars

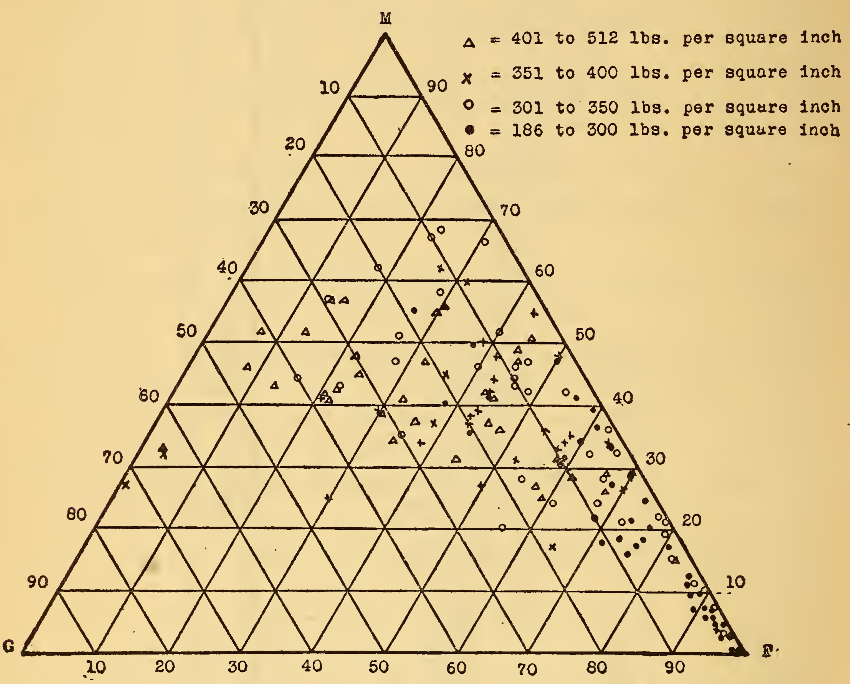

FIG. 13.—*Showing the fineness, according to Feret, of sands having a tensile strength between 186 and 512 pounds.* (*See p. 32*)

made from them. The percentage of voids, density, and weight per cubic foot are closely related. Generally the lower the voids the greater is the density and the greater the strength of the resulting mortar. Sands having 30 to 35 per cent voids are usually fairly well graded. There are not many sands included in this investigation which had less than 33 per cent of voids.

The "uniformity coefficient" appears to be of less value as a criterion of the quality of a sand for use in concrete than the granular analysis.

A consideration of all the physical properties of sands with relation to the strength results, indicates that it is impossible to adopt any specification for sand, based upon these characteristics,

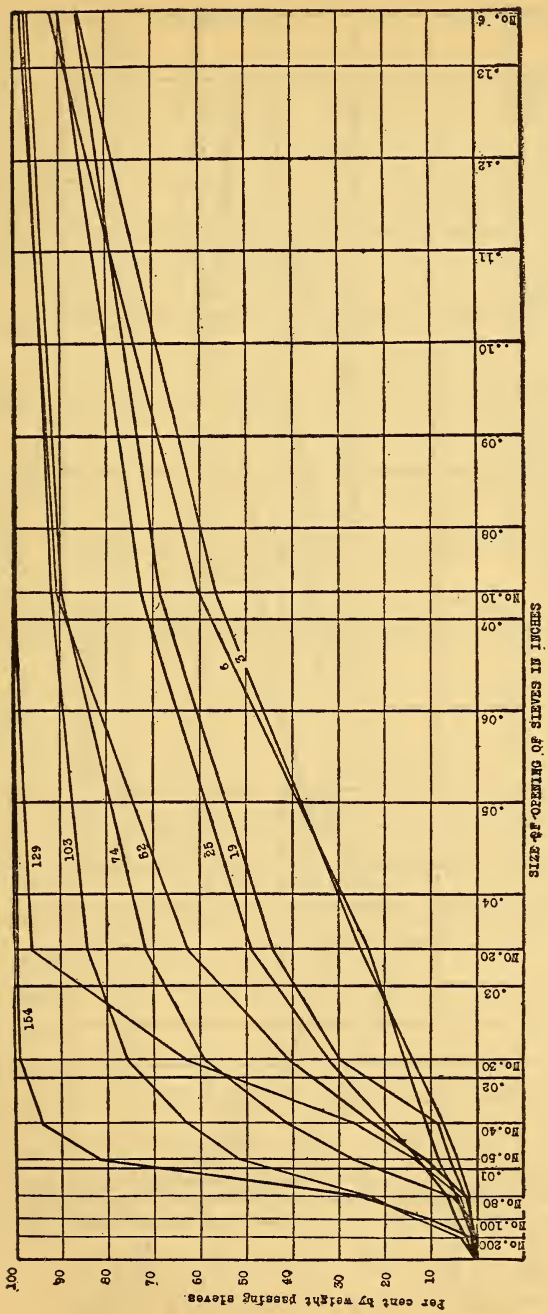

FIG. 14.—*Curves showing the typical gradation of fine and coarse sands. (See Table 1 for complete results.) (Figures on curves represent sample numbers as given in Table 1)*

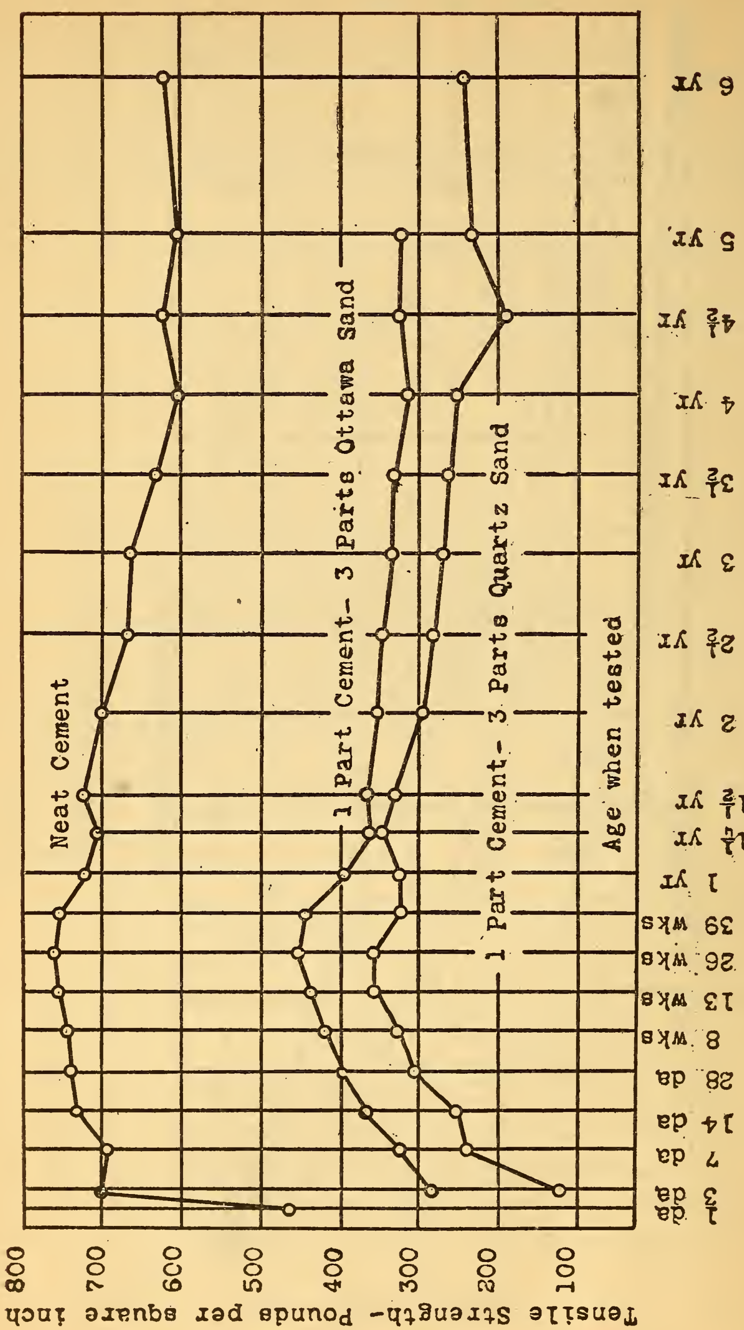

FIG. 14a.—*Long time tensile tests of neat Portland cements and mortars.* (*See Table 7a*)

which will not reject sands which may be satisfactory in use, or which may not admit materials that may be proven unsatisfactory by further tests.

2. PORTLAND CEMENT CONCRETE MIXTURES

(A) Quality as Affected by the Type of Aggregate.—The results shown in Tables 8 to 17 include results of tests on concrete cylinders and cubes, made of various proportions of cement and all types of aggregate and tested at periods up to one year. Throughout these tables it will be found that only a few sands were used as fine aggregates with the many coarse materials, so that a more direct comparison of results may be made than when different sands are used with the different coarse aggregates. In most cases there is not a great difference in the quantity of water used for the different materials. In every case an attempt was made to obtain the same wet or "mushy" consistency so that the percentage of water was varied slightly due to differences in the aggregates.

Throughout these tables the proportions are reported in volume measure, but uniformity was insured at the time of mixing by weighing all materials, whose weight per unit volume had been carefully determined previously.

The compressive strength, yield point, and modulus of elasticity of several materials are given in Table 8, which includes the results of tests on 18 limestones, 11 gravels, 3 granites, 2 trap rocks, and 1 cinder, made up into concrete of 1:2:4 proportions and molded in the form of standard 8 by 16 inch cylinders.

At the end of four weeks the range of compressive strength, in pounds per square inch, was as follows:

Limestone, 1276 to 3984, range of 213 per cent.
Granite, 2376 to 3054, range of 29 per cent.
Gravel, 888 to 4126, range of 354 per cent.

Had there been more granites tested it is very likely that the range of values at this period would have been greatly increased. Many of the values obtained with the limestone exceeded the highest value obtained with granite, but the average is greatly reduced on account of many low-testing limestones being included. With very few exceptions there is a gradual increase in strength with age and those limestones tested at the two-year periods were still increasing at that time and show unusually high values. These results show that there is as great variation in the strength of aggregates of the same type as between aggregates of different

types and it can not be said in general that any particular type is superior to all aggregates of any other type. This is shown diagrammatically in Fig. 15.

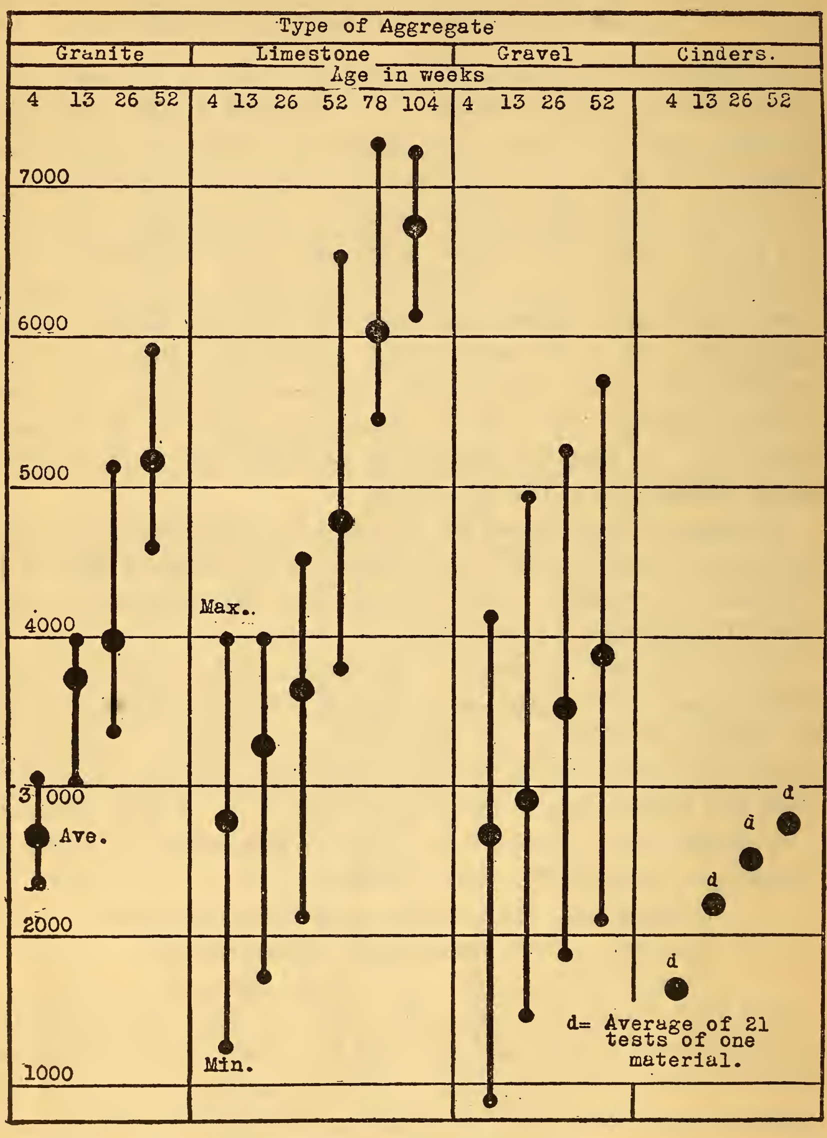

FIG. 15.—*Average and range of compressive strengths of 1–2–4 concrete made of a large number of aggregates of different types. (Test pieces, 8 by 16 inch cylinders. See Table 8)*

Table 9 shows the results of tests on the 1:3:6 proportion concrete using practically the same aggregates as in the 1:2:4 concrete, results of which were given in Table 8. Here, again, it is

found that the compressive strength at the age of four weeks may vary as much as several hundred per cent not only among aggregates of the same type, but between those of different types. For example, at the four-week period granite 317 and limestone 160 showed a variation in strength of nearly 300 per cent. The same sand, 181, was used with both of these aggregates.

Tables 10 and 11 contain results of tests on 1:1:5 and 1:2:7 concretes made from a few of the aggregates included in the preceding tables. The range of values is not so great, due to the inclusion of a smaller number of materials of the limestone and gravel type. As in the preceding tables, the yield points and initial moduli of elasticity show a constant increase with age with a few exceptions.

The values shown in Table 12 are especially interesting in that the proportions of materials used are based upon the voids in the aggregate, a method often used in practice when the voids are known. In this work the amount of cement used was 10 per cent in excess of the calculated voids in the sand, as determined in accordance with methods previously described, and the amount of mortar used was 10 per cent in excess of the calculated voids in the coarser aggregate. Sand 183 was used in most of the theoretical mixtures and the same sand was used with several of the same aggregates in the 1:2:4 and 1:3:6 proportions, which allows a direct comparison, as shown in Table 13.

From the results given in Table 13 it will be seen that with only one or two exceptions the theoretical mixture, using the same sand throughout, shows greater strength at all periods than the 1:3:6 mixture, but in every case the 1:2:4 mixture is superior to both. The strength of the theoretical mixture is approximately what might be expected from a proportional reduction in the ratio of cement to the total quantity of coarse aggregate when the proportion of coarse aggregate to fine aggregate is approximately as 2 to 1. The theoretical proportions, calculated by this void method for gravel aggregates of Table 12, require an especially large quantity of coarse aggregates, varying from 6.2 parts to 11.4 parts. Since these aggregates which, when used in this manner, require large volumes of coarse aggregate, have usually a low compressive strength, it should be kept in mind that any reduction in the proportions of cement to total aggregate of maximum density usually results in a corresponding reduction in strength.

The void method of proportioning concrete is often used upon the assumption that great density is obtained; that is, it is assumed

that the total volume of the fine and coarse aggregate combined is equal to the original volume of the coarse aggregate. While density tests were not made on the concretes made from these particular materials a comparison of the weights per cubic foot

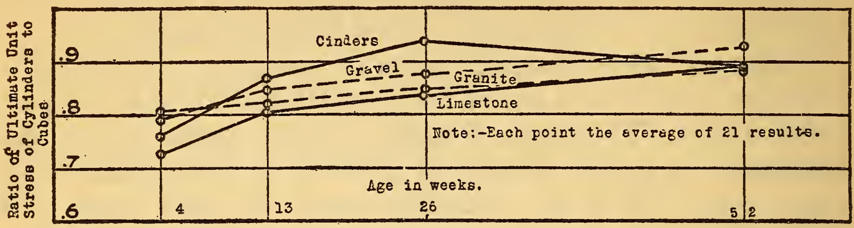

FIG. 17.—*Effect of age on the ratio of the compressive strength of 8 by 16 inch cylinders to 6-inch cubes.* (*See Table 17*)

of the theoretically proportioned concrete and the 1:2:4 and 1:3:6 concretes of the same aggregates indicate that there is not much difference in density. Fig. 16 shows why the void method of proportioning is of no value, as the relative sizes of the several

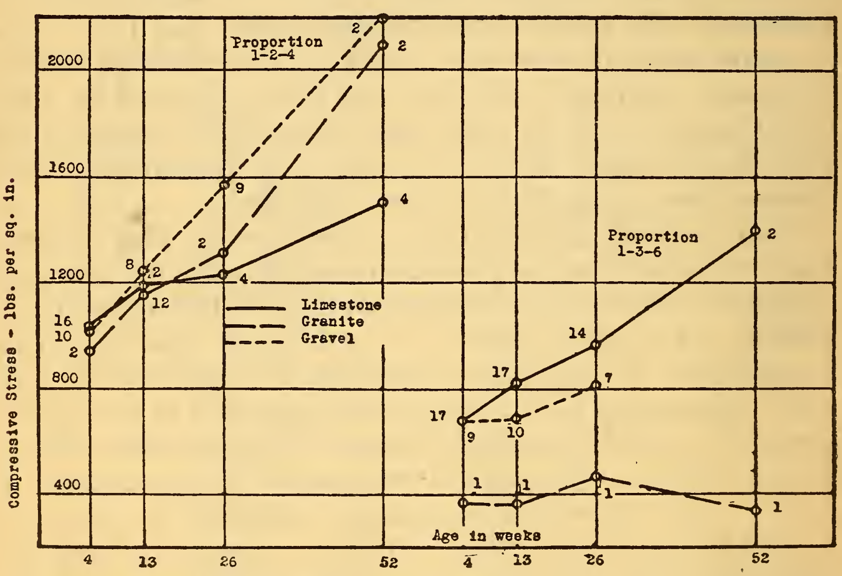

FIG. 18.—*Variation of yield point with age of 1–2–4 and 1–3–6 concretes in which granite, gravel, and limestone aggregates were used.* (*Test pieces, 8 by 16 inch cylinders. See Tables 8 and 9.*) (*Figures denote the number of materials averaged. The number of test pieces represented is at least three times the number of materials*)

materials which are combined is not considered and it is assumed that a quarter-inch diameter stone will fill the voids in stone particles 1 inch or smaller in diameter without wedging them apart. Due to the wedging action of the small particles the large

aggregate is forced apart so that the density of the mixture, after water and cement are added, is certain to be less than that calculated excepting under extraordinary conditions.

In order that the concrete may be worked into place with the usual methods of handling, it is necessary to "oversand" the mixture to a certain extent. When an excess of sand is not present, it is almost impossible to secure a dense mass free from large voids and air pockets, although calculations may indicate that such a combination of sizes should give the denser concrete. A slight increase of the sand content over that theoretically required for

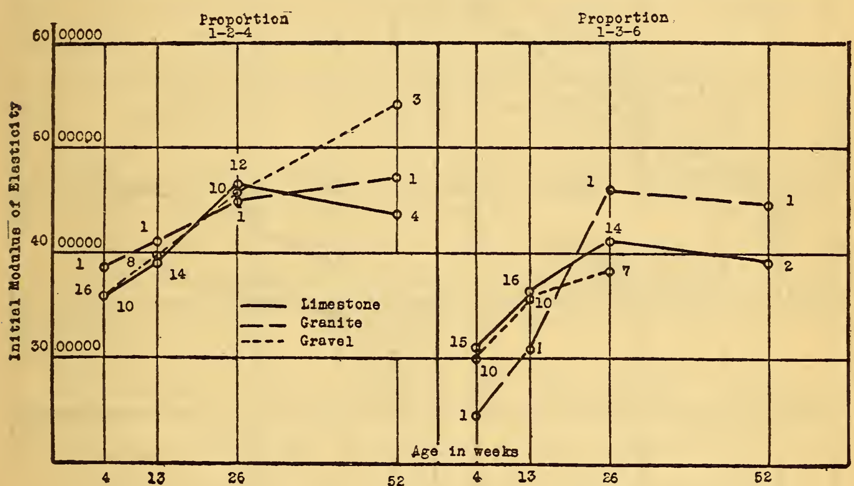

FIG. 19.—*Variation of initial modulus of elasticity with age of 1–2–4 and 1–3–6 concretes in which granite, gravel, and limestone aggregates were used. (Test pieces, 8 by 16 inch cylinders. See Tables 8 and 9.) (Figures denote the number of materials averaged. The number of test pieces represented is at least three times the number of materials)*

maximum density will show a greater calculated void space, but in practice best results will be secured with such a combination.

Table 14 includes tests of all cylinders made up of the odd proportions which have not been included in the preceding tables due to the small number of tests of any single mixture. Direct comparison can be made between the results of this table and those of the preceding tables.

The results of compression tests on 6-inch cubes are shown in Tables 15 and 16. In these tables practically all the aggregates used in the cylinder tests are represented and each material was used in a number of different proportions. In Table 15 are shown the four-week results of tests on proportions ranging from 1 : 0 : 6

to 1 : 4 : 2 and 1 : 0 : 9 to 1 : 4 : 5. Table 16 contains the results of all tests up to one year of the theoretical, 1 : 2 : 4 and 1 : 3 : 6 proportions, which were the only mixtures tested at periods later than four weeks.

The results here, as in the case of the cylinder tests, show that it is impossible to state in general that any one type of aggregate is superior to another as an aggregate for concrete, especially when a sufficient number of aggregates to fairly represent the range of quality of that type are included. The cubes have greater strength

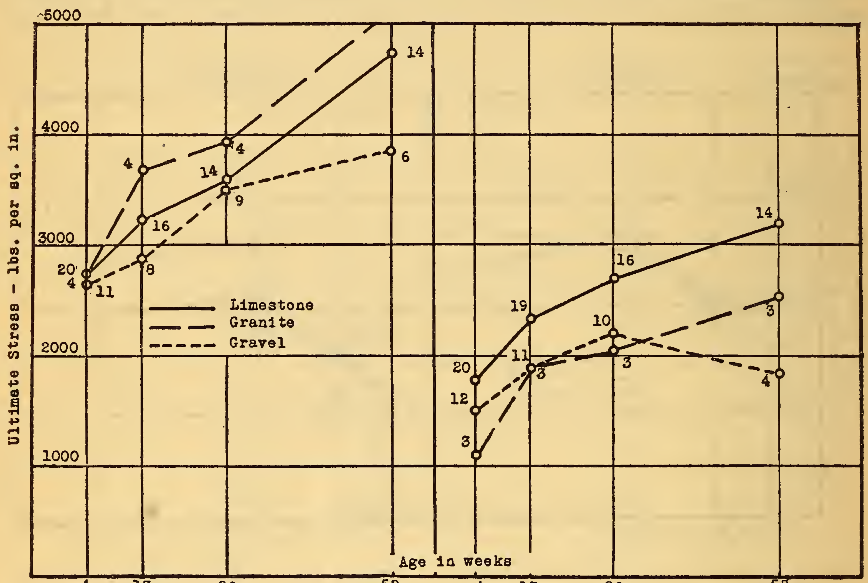

FIG. 20.—*Variation of compressive strength with age of 1–2–4 and 1–3–6 concretes in which granite, gravel, and limestone aggregates were used. (Test pieces, 8 by 16 inch cylinders. See Tables 8 and 9.) (Figures denote the number of materials averaged. The number of test pieces represented is at least three times the number of materials)*

than the cylinders, as is seen by comparing the results of these tables with those of Tables 8 to 14. A further comparison is made in Table 17 and the relation of the ultimate strength of the cylinders to cubes is shown in Fig. 17.

In Table 19 the strength attained by 1 : 2 : 4 concrete using seashore sand, of which 99 per cent passed the No. 50 sieve, should be noted. At the four-week period this concrete exceeded the value of 2000 pounds per square inch compressive strength, which is ordinarily considered as standard for that mixture, and there is a constant increase in strength at later periods.

The effect of age on the ratio of yield point to ultimate compressive strength of granite, gravel, and limestone concretes of 1:2:4 and 1:3:6 proportions are shown in Fig. 18.

In Fig. 19 is shown the variation with age of the average initial modulus of elasticity of granites, gravels, and limestone concretes of 1:2:4 and 1:3:6 proportions.

Fig. 20 shows the average ultimate compressive strength of granite, gravel, and limestone concretes in 1:2:4 and 1:3:6 proportions up to the age of one year.

Typical stress strain curves are shown in Fig. 21 for one aggregate which seems to be representative of many of the aggregates at the age of one month for various proportions.

All results of tests so far considered would indicate that the type of aggregate is no guaranty of strength in concrete, even though strength were alone due to the materials used, but that qualities such as hardness, shearing strength, and gradation of particles are of even more importance.

(B) Quality as Affected by Method of Mixing.—In Table 18 are shown two series of results of tests on concrete cylinders in which all variables were eliminated except the workmanship in mixing the concrete.

All materials except mixing water were weighed out by the laboratory force and turned over to the forces of three concrete construction companies designated by the letters A, B, and C. A similar lot of materials in each case was mixed by the laboratory force.

Each company used its own judgment in the process of mixing and in the addition of water, the instructions to each requiring that the work be carried out just as in actual construction work. In every case a record of the amount of water used was kept by the laboratory force.

In order that the molding might be done in a uniform manner, and to eliminate any errors in results which might be due to different methods of molding, all compression test pieces were made by the laboratory force and stored under uniform conditions as described below.

The test pieces marked "outside" were molded in the laboratory and after 48 hours the molds were removed and the cylinders placed outside, where they were exposed to the weather. Those marked "inside" were molded in the laboratory and after 24 hours were placed in the damp room, where they were sprinkled three times daily.

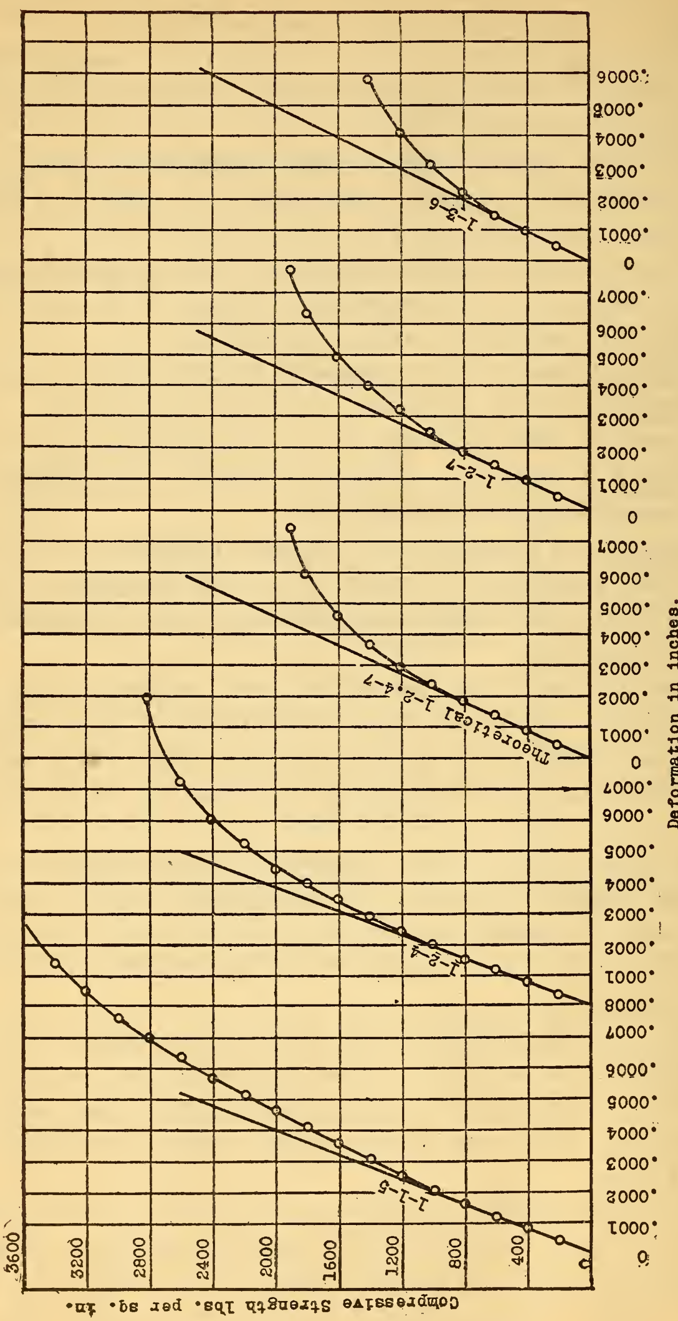

FIG. 21.—*Typical stress strain curves for various proportions of the same aggregates in concrete. (Test pieces, 8 by 16 inch cylinders.) Age, 28 days. Aggregates: Sand 183 and gravel 35*

The exact method of mixing the concrete as employed by each contractor was as follows:

Company A.—The hand-mixed concrete was prepared by spreading the stone out in a thin layer on a cement floor, spreading the sand out on top of the stone and the cement on top of the sand. The material was then formed into a pile by four men shoveling in the outer edges of the layers. The material was then turned into a second pile by two men, from which two others would turn it into a third. This made one partial dry mix by shoveling up the original pile and two thorough dry turnings.

Water was then added from a bucket, the shovelers meanwhile cutting the pile down in roughly concentric circles, until about three-fourths of the total water was added.

The wet material was then turned twice in the same manner as the dry material, water being added from a bucket as the foreman thought necessary. In order to arrive at the percentage of water that was used, the weight of water contained in a full bucket was determined and a record kept of the number of buckets used in each batch.

In appearance the consistency was a trifle wetter than that described as quaking consistency.

The machine-mixed concrete was prepared in a 1 cubic yard Chicago cube mixer and the dry material in the proper proportions was delivered to the charging hopper of the mixer by the laboratory force. The material on being dumped into the mixer received scarcely any dry mixing, water being added almost immediately. The water was run into the mixer from a barrel which rested on a platform scale above the mixer. The contractor was instructed to run in water until he had obtained what he considered the desired consistency, after which the weight of water that was used was read from the scale and recorded by the laboratory force.

The mixer was dumped as soon as the proper amount of water had been run in.

Company B.—A slightly different method was followed when mixing the concrete for inside and outside use. The change in the method of mixing was not made because the concrete was to be used outside, but because the contractor thought he could work more rapidly with the new method of mixing.

All hand mixing of concrete used outside was done on a cement floor by four men with shovels. The dry material was delivered on the floor in the same order and was mixed in the same manner

as was that used by company A. It was cut down into a layer about 8 inches deep with the edges somewhat higher than the center. Water was then run in from a hose attached to a water barrel mounted on a platform scale, the concrete at the same time being cut into with a spade. Almost all the water was added at this time, the remainder being put in while the wet concrete was being mixed. The amount of water to be used was left entirely to the judgment of the contractor, a record of the amount used being kept by the laboratory force.

The edges of the pile were thrown in toward the center, after which the concrete was mixed by shoveling into two piles, being cut into with shovels at the same time.

For the concrete used inside the dry material was delivered on the floor in the same order as previously described, but each material was not first spread out before the next was added. When all the material had been delivered, it was, consequently, an irregular pile instead of in three uniform, comparatively thin layers. From this pile two men turned the dry material into a second, while a third man continued to shovel the first pile into a pyramid, thus turning some of the material before it was turned into the second pile. The dry material was mixed twice in this manner.

Instead of spreading the material out into a shallow trough before turning, only a portion of the dry material was leveled off on one side of the pile and water added from a hose while two men turned the mixture. When sufficient water had been added the concrete was turned twice in the same manner as was the dry material.

For the machine-mixed concrete the contractor followed the same method as the previous contractor, in that water was run into the mixer as soon as the dry material was dumped into it by the charging hopper. As soon as all the water had been added, the mixer was tilted and the concrete dumped on the cement floor. This was the most fluid concrete used in these tests, the percentage of water being almost 14 per cent, while the next lowest was about 11 per cent. The concrete was so wet that when dumped on the floor a mass of about 0.6 cubic yards would lie in a pile about 4 inches high, while the surface of the gravel appeared comparatively clean, little mortar seeming to stick to it.

The compression cylinders were molded by the laboratory force by placing the concrete in approximately 3-inch layers and tamping. The agitation of such a wet material composed of

particles differing greatly in size resulted in its separation, so that when the cylinders were tested the top of the cylinder was found to consist of almost all the gravel mixed with a little mortar, while the bottom contained the cement, sand, and smaller aggregate.

Failure took place on the line separating tne fine and the coarse material, and the strength is in all probability not governed entirely by the percentage of water.

Company C.—The hand-mixed concrete was prepared on a cement floor by four men with shovels. A layer of stone was first placed on the floor, then a layer of sand, and lastly the required amount of cement. The pile was then shoveled out into a layer about 8 inches deep. Four men started at the four corners of the pile, two in each case shoveling toward each other. This separated the larger layer into two piles. After the concrete had been separated in this way, two men shoveling from each of the two piles turned the dry concrete back into one pile, after which it was spread out in a layer about 8 inches deep.

Nearly all the water was then added, the concrete being cut into with shovels to aid the penetration of the water to the interior. The material was mixed wet in a manner similar to the dry mix, more water being added whenever the concrete seemed a little dry.

The consistency of the concrete used corresponded very closely to that described in this paper as mushy, although it was slightly wetter.

The machine-mixed concrete was prepared in substantially the same manner as was that used by the preceding contractors. Water was added to the dry material as soon as it had been dumped into the mixer and the mixer tilted as soon as all the water had been added.

Laboratory force.—The method employed in preparing the machine-mixed concrete was to dump the dry materials into the mixer, which was turned for two minutes when the water was added to give a quaking or mushy consistency and the mixing continued for three minutes more. As the material was dumped on the floor it appeared somewhat lumpy and stood in a pile with steep slopes.

The results of tests are shown in the table for both 1:2:4 and 1:3:6 mixtures. The latter included both gravel amd limestone concretes, both hand and machine mixed; the 1:2:4 concrete was made of gravel aggregate and was machine mixed. Since the

curing conditions were entirely different, no comparison can be made between the cylinders stored "outside" and those stored "inside" with respect to workmanship or method of mixing. The tests of cylinders stored under similar conditions, however, give a direct comparison of the range of values which may be expected when only workmanship in mixing is concerned.

The following results were obtained with 1:3:6 gravel and limestone concrete mixtures:

(*a*) *Hand-Mixed 1:3:6 (by volume) Gravel Concrete Stored Exposed to Weather.*—At four weeks the average of each company's output had a range from 441 to 864 pounds per square inch, or 96 per cent of the lowest average, which is that of company B. The range of results of single test pieces is 573 pounds, or 130 per cent. At 13 weeks the range of averages is from 577 to 852 pounds, or 48 per cent; and of single results is 439 pounds, or 77 per cent. At both periods the highest strength was obtained by company A, second by company C, and third by company B, inversely in order of the amount of water used. There was no increase in strength at the second period of the concrete made by company A, while company B, using the largest amount of water, showed the greatest gain in strength with age.

(*b*) *Hand-Mixed 1:3:6 (by volume) Gravel Concrete Stored in Laboratory.*—At four weeks the range of average values for the various contractors was from 384 to 622 pounds per square inch, or 62 per cent of the lowest, and the range of single results was 374 pounds, or 86 per cent.

At 13 weeks the range of averages was from 748 to 1313 pounds, or 75 per cent, while the range of single results was 1217 pounds, or 217 per cent. Company C, at four weeks, using 9.4 per cent water (the minimum), obtained an average strength of 384 pounds, by far the lowest of the three, while at 13 weeks company B, using 10.8 per cent water (the minimum) at this period, obtained a maximum strength of 1313 pounds, considerably in excess of the other two companies. At this age company C obtained with 11 per cent of water a value of only 827 pounds per square inch, which is only slightly higher than company B obtained at four weeks with only 0.2 per cent less of water.

(*c*) *Machine-Mixed 1:3:6 (by Volume) Gravel Concrete Stored Exposed to Weather.*—The only set of test pieces treated in this manner were prepared by the laboratory force and can best be compared with the "Hand-mixed cured outside," first referred to. At four weeks, using 9.8 per cent water, the results obtained were

exceeded by company A with 10.9 per cent of water, but at 13 weeks the results obtained by company A were exceeded about 25 per cent, using only 0.1 per cent less water.

(*d*) *Machine-Mixed 1 : 3 : 6* (*by Volume*) *Gravel Concrete Stored in Laboratory.*—This set includes specimens made from concrete prepared by the laboratory force, as well as by the contractors. At four weeks the range of averages was from 558 to 1027 pounds, or 84 per cent, and the range of single results was 588 pounds, or 109 per cent. At 13 weeks the range of averages was from 937 to 1606 pounds, or 71 per cent, and the range of single values was 768 pounds, or 88 per cent.

The highest values at both periods were obtained by the laboratory force, which used the lowest percentage of water in mixing while the lowest results were obtained by company B, which used the highest percentage of water. At both periods and including all four sets of results the strength varied inversely as the percentage of mixing water, with the exception of the results of company B. The results obtained by machine mixing were from 30 to 90 per cent in excess of those obtained by hand mixing. It is very probable that the failure of company B to obtain superior results with the machine was due to the large excess of water used.

(*e*) *Hand-Mixed 1 : 3 : 6* (*by Volume*) *Limestone Concrete Stored Exposed to Weather.*—The concrete prepared by the laboratory force was machine mixed. The range of average results at four weeks was from 390 to 951 pounds per square inch, or 144 per cent, and the individual results 603 pounds, or 166 per cent. At 13 weeks the range of averages was from 556 to 1222 pounds per square inch, or 120 per cent, and for the individual was 843 pounds, or 160 per cent. Here, again, the strength varied inversely as the percentage of water. At the 13-week period the range of results obtained by company C was especially great, being 794 pounds, or 137 per cent. In all cases there was a good increase in strength at the 13-week over the 4-week period.

(*f*) *Machine-Mixed 1 : 2 : 4* (*by Volume*) *Gravel Concrete Stored Exposed to Weather.*—At four weeks the range of averages was from 1443 to 2312 pounds per square inch, or 103 per cent, and the range of single results was 1378 pounds, or 113 per cent. At 13 weeks the range of averages was from 1890 to 2809 pounds per square inch, or 53 per cent, while the range of individual results was 1023 pounds, or 59 per cent.

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The highest strength was obtained by the laboratory force followed by companies C, B, and A. The smallest amount of water, 8.9 per cent, was used by the laboratory followed by companies C and B, both using 9.4 per cent, and company A with 11 and 10.3 per cent.

In the case of the laboratory results, the increase at 13 weeks is slight, while there was a slight decrease on the part of company C. Good increases in strength were shown by both companies B and A, and it is noticeable that in the case of company B the value at four weeks was 20 per cent less than that of company C, which used the same amount of water, and at the 13-week period the strength of concrete prepared by company B was still below that attained by company C at the 4-week period. This is a case where two concretes have practically the same ultimate strength, attained in one case by increasing with age and in the other by the falling off of a high initial strength. This average result is not due to a single abnormally low result at the 13-week period, but all test pieces showed lower compressive strengths than at the 4-week period.

(*g*) *Machine-Mixed 1:2:4 (by volume) Gravel Concrete Stored in Laboratory.*—At the 4-week period the range of averages was from 1443 to 2312 pounds per square inch, or 60 per cent, and of the single values was 1327 pounds, or 114 per cent. At 13 weeks the range of averages was from 1890 to 2809, or 53 per cent. Again, the strength varies inversely as the amount of mixing water. The gain in strength at the 13-week period over the 4-week period is greater in every case than in the preceding set.

The values given in Table 18 are shown graphically in Fig. 22.

These results show that the greatest variation in strength is due to the use of varying quantities of water, but, with practically the same quantity of water and with all other conditions the same excepting the actual mixing of the materials, variations of as much as 70 per cent in compressive strength are obtained.

(C) Quality as Affected by the Method of Molding.—In Table 19 are shown results of tests on concrete cylinders molded above and below water. In many cases it is not possible to remove water readily from places in which concrete is to be deposited and it becomes necessary to place the concrete through water. One common method in use is to employ the pipe or tremie, whose lower end is kept just below the surface of the mass being deposited, so that there is no intermixture of the concrete and the surrounding

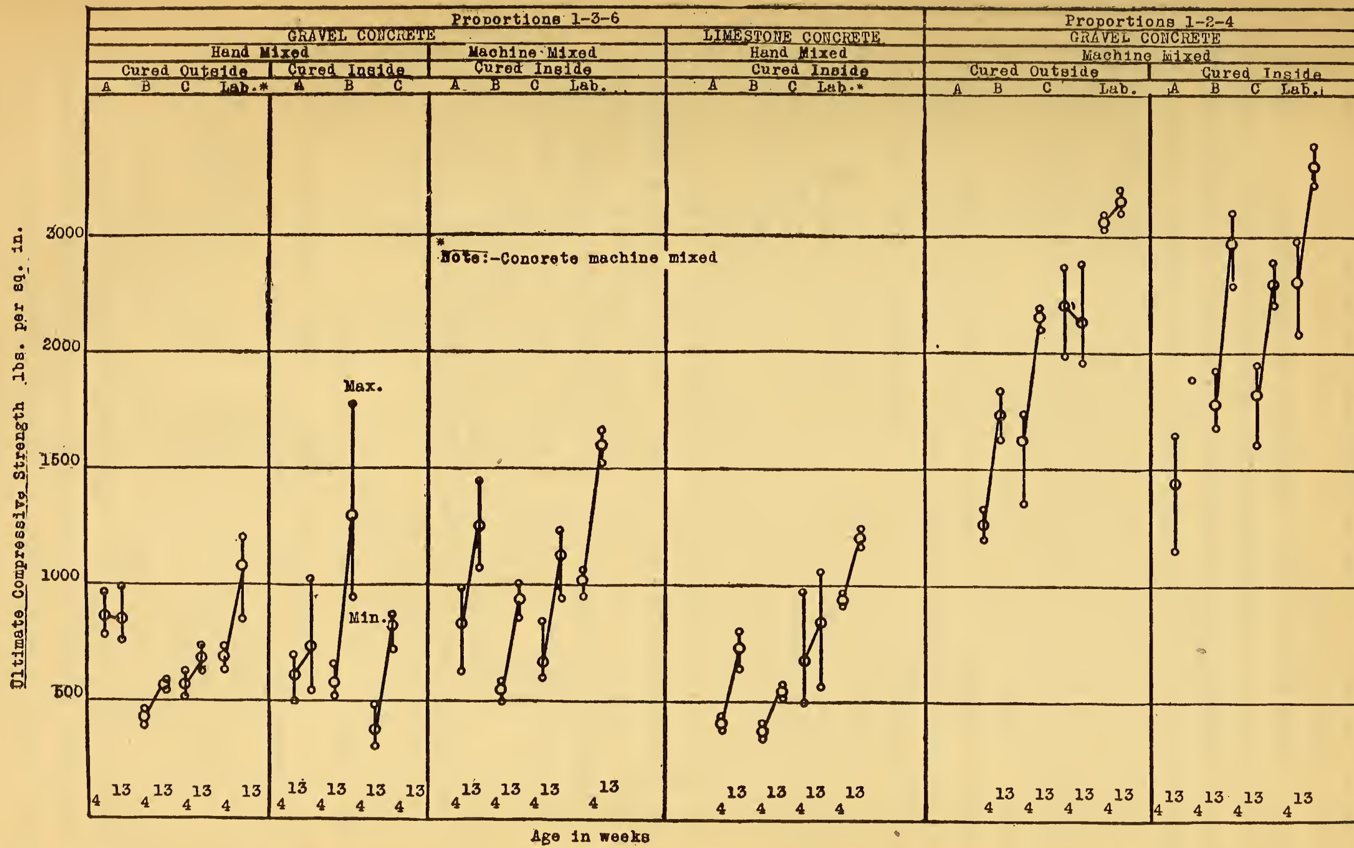

FIG. 22.—*Variation in compressive strength of 1–2–4 and 1–3–6 concretes prepared with the same materials but mixed as in practice by three different contractors A, B, and C, and the laboratory force. Cement and aggregates were weighed by the laboratory force, the water and materials mixed by the forces designated. All test pieces were molded by the laboratory force. (Test pieces, 8 by 16 inch cylinders. See Table 18)*

water while being conveyed to the point of deposit. The operation of filling the cylinder molds in this particular series of tests has already been described.

The results indicate that there is a considerable reduction in strength of concrete deposited in this manner, especially in the case of the leaner mixtures, such as the 1:3:6, in which the reduction was over400 per cent at the one-year period. This result should be considered with caution, however, as it is probable that with larger masses and a large tremie the surface effect of the form would be negligible and there would be less segregation than occurred with the specimens molded. In the case of the 1:2:4 proportion the concrete placed through the tremie reached about 70 per cent of the value obtained from concrete deposited in the usual manner, and there was a constant gain in strength at each period of testing. The chief problem is to keep the surrounding water from segregating the materials while the concrete is deposited, as is shown by the tests on concrete cylinders which were immersed with the mold immediately after the concrete was deposited. The strength in these cases was only slightly less than that of specimens molded and stored in a moist atmosphere in the usual manner.

(D) Quality as Affected by Consistency.—As was indicated in the previous section on "mixing," the strength of a mortar or concrete, especially at the early periods, is effected to a considerable extent by the consistency or the proportion of mixing water.

The results given in Table 2 show the effect of varying the amount of water in a mortar of various proportions. In the mixture of 1 part cement to 2 parts sand there is a difference in strength at 28 days between the plastic and dry consistencies of 2499 pounds, or 275 per cent, while at 6 months the difference is 1917 pounds, or about 120 per cent.

The range of values for the leaner mixtures is less than the above, but is large enough to indicate that consistency is one of the variables which largely controls the strength.

In Table 20 are shown results of tests of concrete cylinders made with varying percentages of mixing water. These results are incomplete and unfortunately were not carried out as originally planned. They are sufficient, however, to indicate that the strength at the early ages is materially affected by the quantity of water used in mixing the concrete. In the case of the limestone concrete maximum strength was obtained with 8 per cent of water and in the other case, with gravel concrete, with 6 per cent of

water. In the case of the limestone concrete it is evident that 3 per cent excess over the amount required for maximum strength causes a reduction in strength of over 50 per cent, while the use of 3 per cent less than the maximum causes a reduction of about 33 per cent. The effect of an excessive amount of water is even more marked where gravel is used as a coarse aggregate.

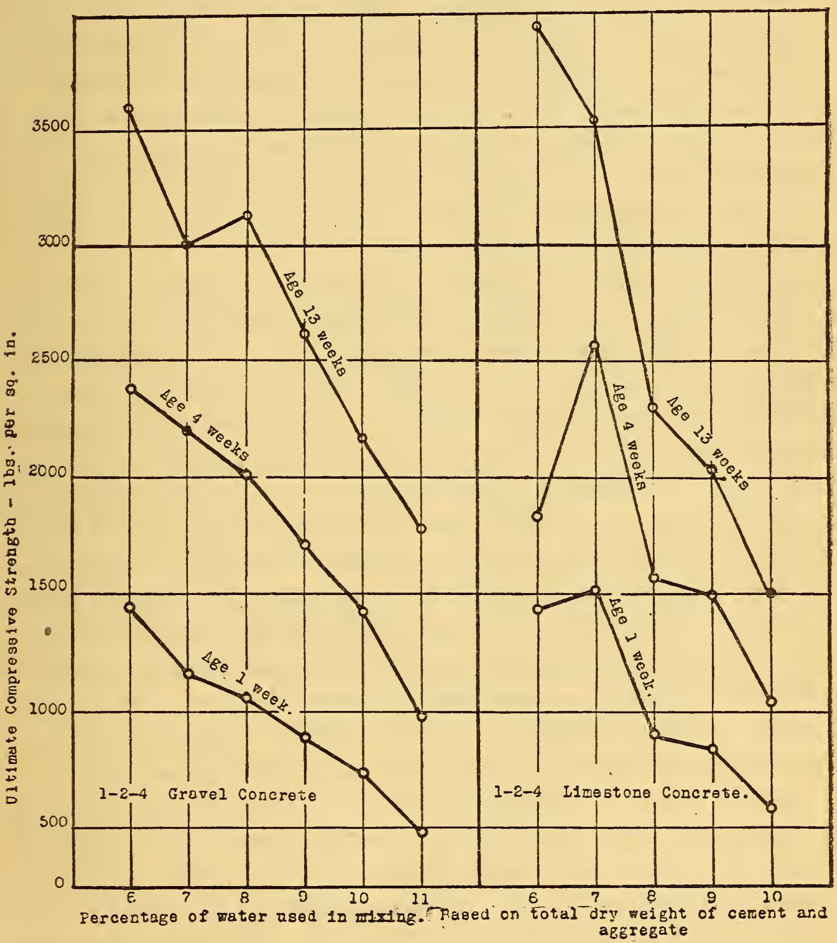

FIG. 23.—*Relation of consistency of mixtures of Portland cement concretes to the compressive strength. (Test pieces, 8 by 16 inch cylinders)*

In Table 21 are given results of another series of tests on gravel and limestone concretes tested at the age of 1, 4, and 13 weeks. These results are substantially the same as those of Table 17. The great variation in strength with quantity of water used in mixing the concrete is strikingly shown in Fig. 23.

A further idea of the effect of varying the quantity of mixing water can be obtained from Table 22, which contains the results of tests on both cubes and cylinders, made up of 1:2:4 mixtures of granite, limestone, and gravel, and a 1:2:5 mixture of cinders, for periods of 4, 13, 26, and 52 weeks. In every case fluid, mushy, and quaking consistencies were used.

In the case of the cube tests it will be found that the quaking consistency gave the highest results in all but a few cases, when it was exceeded by the mushy consistency concrete. The same is also true for the cylinder tests, although in many cases there is little difference between either of the three consistencies. It is noticeable that the strength of the drier mixtures is usually higher at the early periods, and therefore the gain in strength is proportionally less at the 26-week period.

During the past few years it has become the practice on large concrete construction jobs to mix the concrete at a central point and convey the mixture to the various parts of the structure by means of a tower and chutes. That this method has proven very economical for the contractor is shown by its almost universal use on large work; but the quality of the concrete in place has apparently been a secondary consideration. It is possible that good quality concrete is obtained when the materials are handled in this manner, but it is probable that the strength obtained is very much less than what it should be for the same materials properly mixed to a drier consistency. Throughout all the tests included in this paper where fluid and mushy or quaking consistencies are used the mushy or quaking consistencies invariably give the greater strength. The consistency of the concrete normally used in spouting is usually much wetter than any used in these tests.

Another fault of the fluid or watery consistency is its tendency to segregate when placed in the form. The heavy aggregate settles just below the chute or spout, and the soupy mixture of cement and fine sand or dirt, if the aggregate be at all dirty, flows to the outer face and corners of the form. It is this segregation which undoubtedly accounts for the crazing and cracking of the surface of many retaining walls and other similar structures.

In the field there is often formed in concrete structures which are made of watery mixtures a layer of relatively inert fine material, which floats on the surface as the concrete is deposited and is usually left in place between day's work, forming a weak horizontal layer or seam in the wall. This weak layer, if at the top of

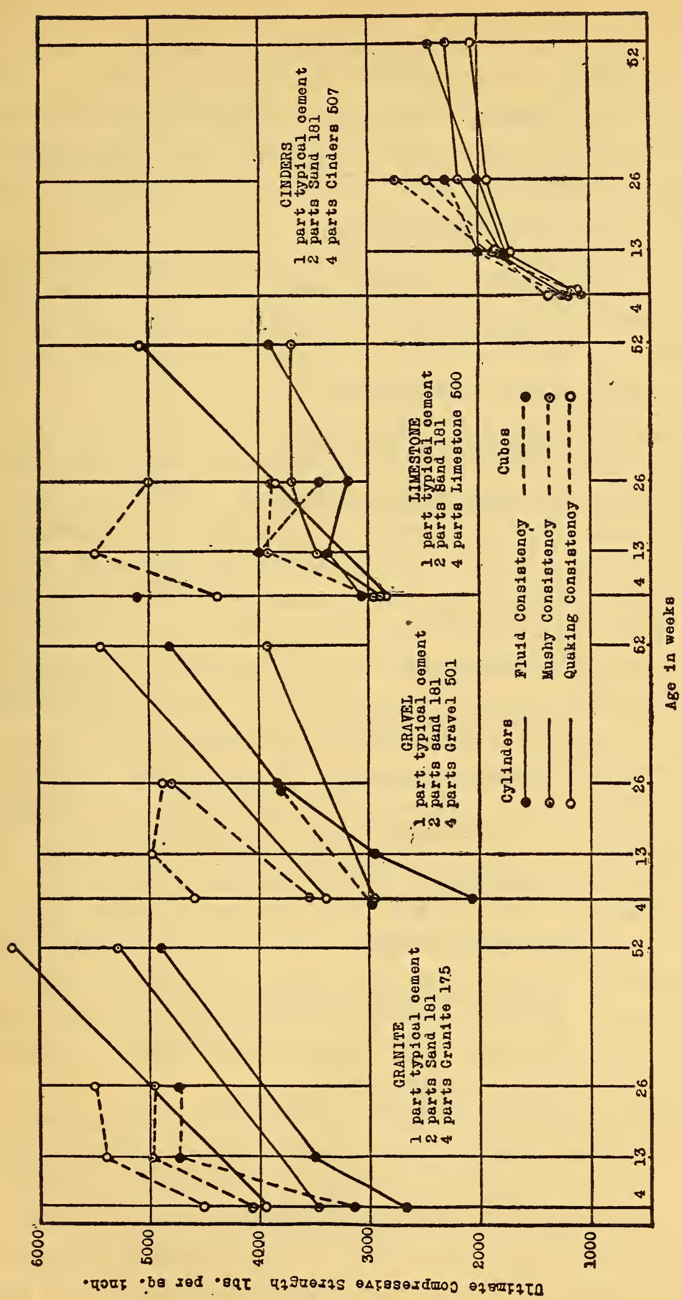

FIG. 24.—*Relation of consistency to compressive strength of 1–2–4 concrete mixtures in which granite, gravel, limestone, and cinders were used. (Test pieces, 6-inch cubes and 8 by 16 inch cylinders)*

the wall, is often referred to as "laitance." It may be from a fraction of an inch to several inches in thickness. If the wall is exposed to the weather, this weak section may be cracked and eroded, as is often observed in retaining walls and arches. This is particularly apparent if the structure is exposed to seepage water. Much of this trouble can be obviated by the use of drier mixtures.

Too much emphasis can not be placed on the objection to using an excess of water in mixing concrete.

The most satisfactory consistencies for concretes, from the standpoint of strength and durability, are the quaking and mushy mixtures and the error should be on the side of using too little rather than too much water, providing the concrete is properly spaded or worked into place in the forms.

Figs. 23 and 24 show that a variation in the amount of water may cause a variation in strength of from 200 to 300 per cent.

(E) Quality as Affected by Density.—In Tables 23 to 25 are shown the results of several series of tests made to determine the relation between compressive strength and density of concrete. Table 23 comprises tests of a large number of different proportions in which stone 388 is combined separately with sand 184 and sand 185. The amount of cement to the total quantity of aggregate in all cases bears the relation of 1 to 6 or 1 to 9. The relation between density and strength for these aggregates is shown in Fig. 25.

Of the concrete made with sand 184 maximum strength was obtained with the 1 : 1 : 5 mixture, while the concrete of maximum density was the 1 : ½ : 5½, which ranked third in strength. The 1 : 0 : 6 mixture was second in strength and third in density. The range in strength among these three was 259 pounds, while the density range was 0.023. Again, the 1 : 2 : 4 mixture shows slightly higher strength than the 1 : 1½ : 4½, whose density was slightly greater. In the 1 : 9 proportion the strength varies as the density, except that the 1 : 1½ : 7½ mixture which is second in density has slightly the highest strength.

Of concretes made up of sand 185 fewer tests were made, but in every case the strength varied as the density of the resulting mixture. From these results it seems reasonable to believe that with any given aggregate and the same proportion of cement, the strength will vary with the density, so that to obtain a concrete of maximum strength with the given materials, a concrete of maximum density should be prepared. This will not hold true for concretes made of two different types or qualities of coarse aggre-

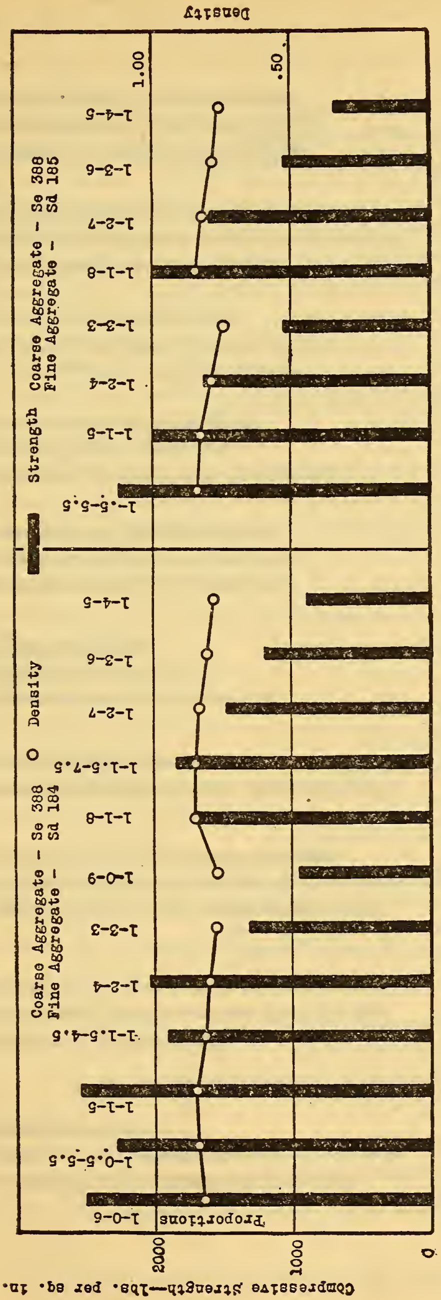

FIG. 25.—*Relation of "density" (solidity ratio) of mixtures of Portland cement concretes to the compressive strength at the age of 4 weeks. (Test pieces, 8 by 16 inch cylinders. See Table 19)*

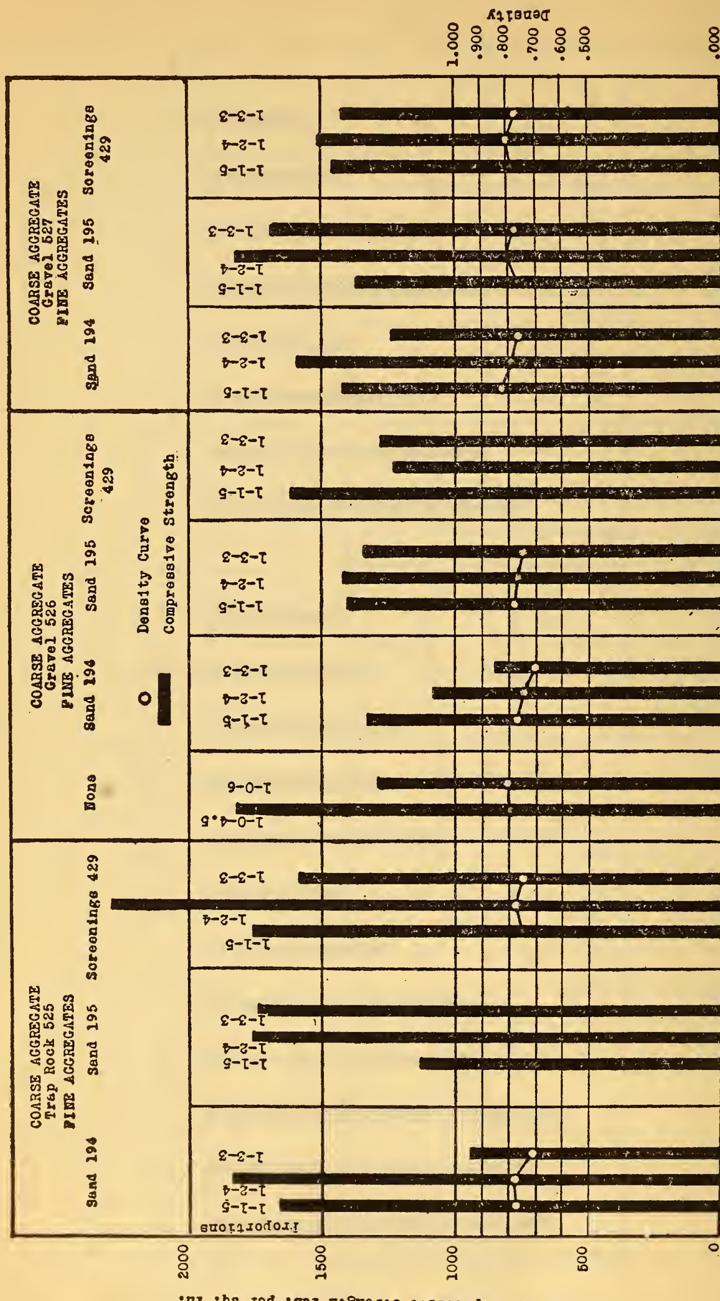

FIG. 26.—*Compressive strengths and densities of 1–6 concretes made with various aggregates. Proportions are in parts by volume. Age when tested, 30 days. Consistency, quaking. (Stored in air and sprinkled twice daily until tested. See Table 26)*

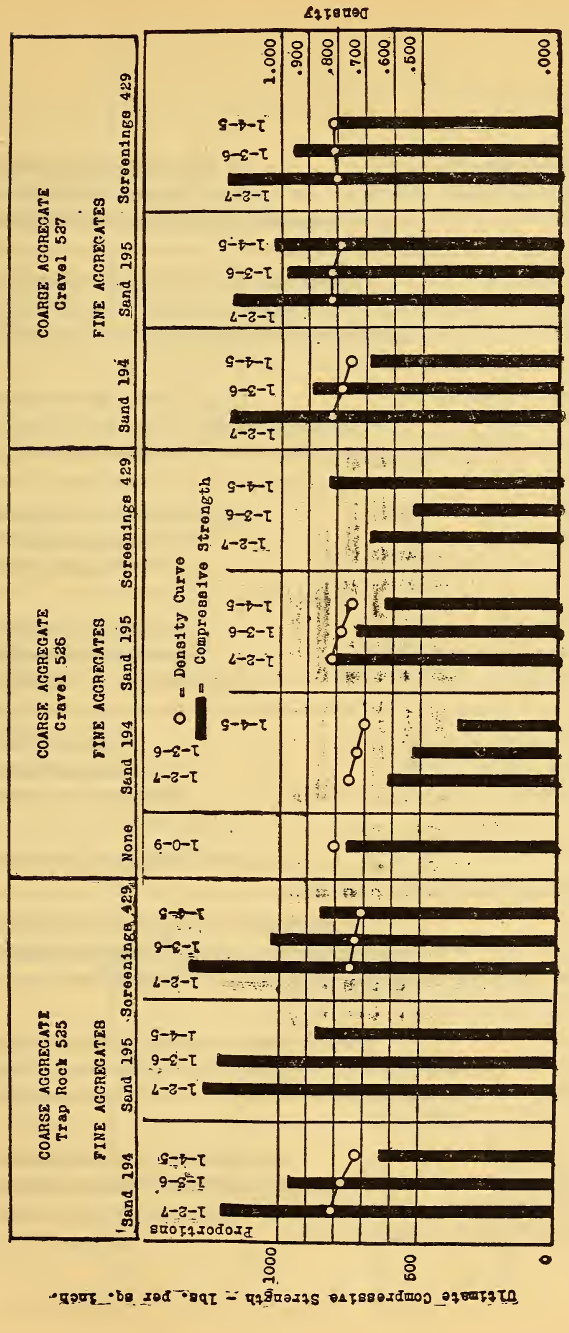

FIG. 27.—*Compressive strength and densities of 1–9 concretes made with various aggregates. Proportions are in parts by volume. Age when tested, 30 days. Consistency, quaking. (Stored in air and sprinkled twice daily until tested. See Table 26)*

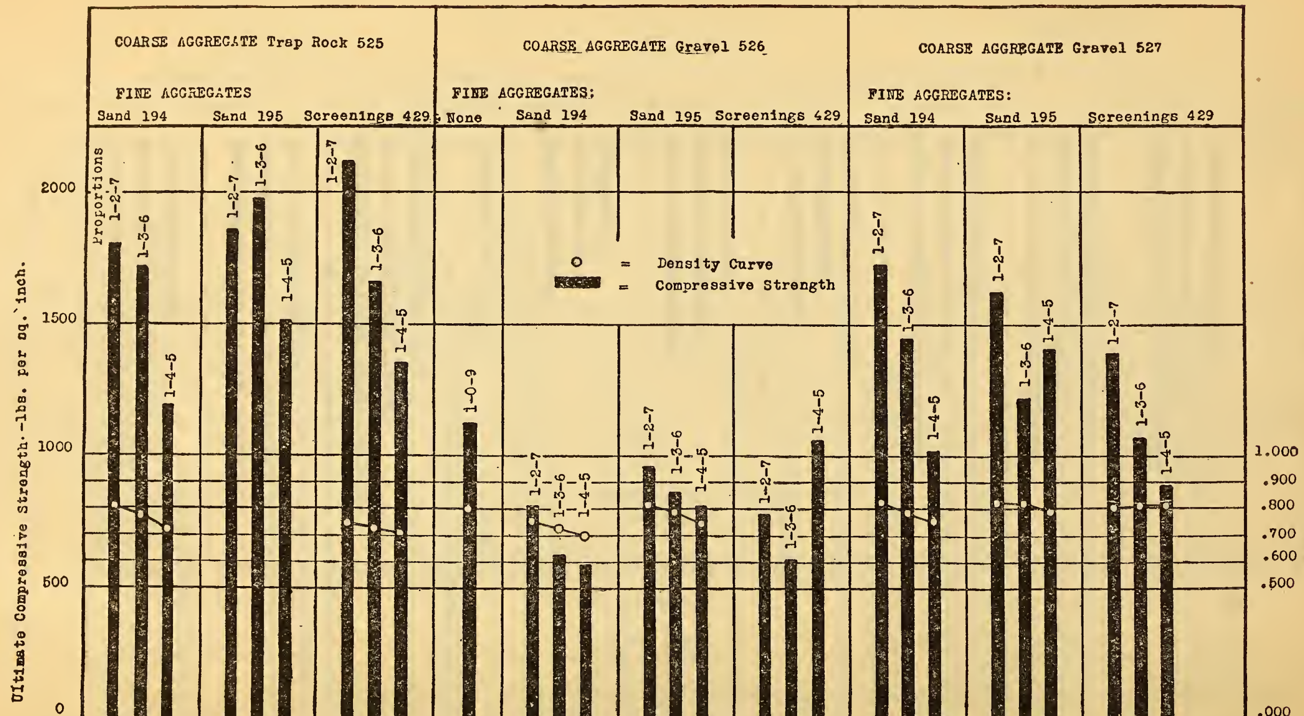

FIG. 28.—*Compressive strengths and densities of 1–6 concretes made with various aggregates. Proportions are in parts by volume. Age when tested, 90 days. Consistency, quaking. (Stored in air and sprinkled twice daily for first 30 days. See Table 26)*

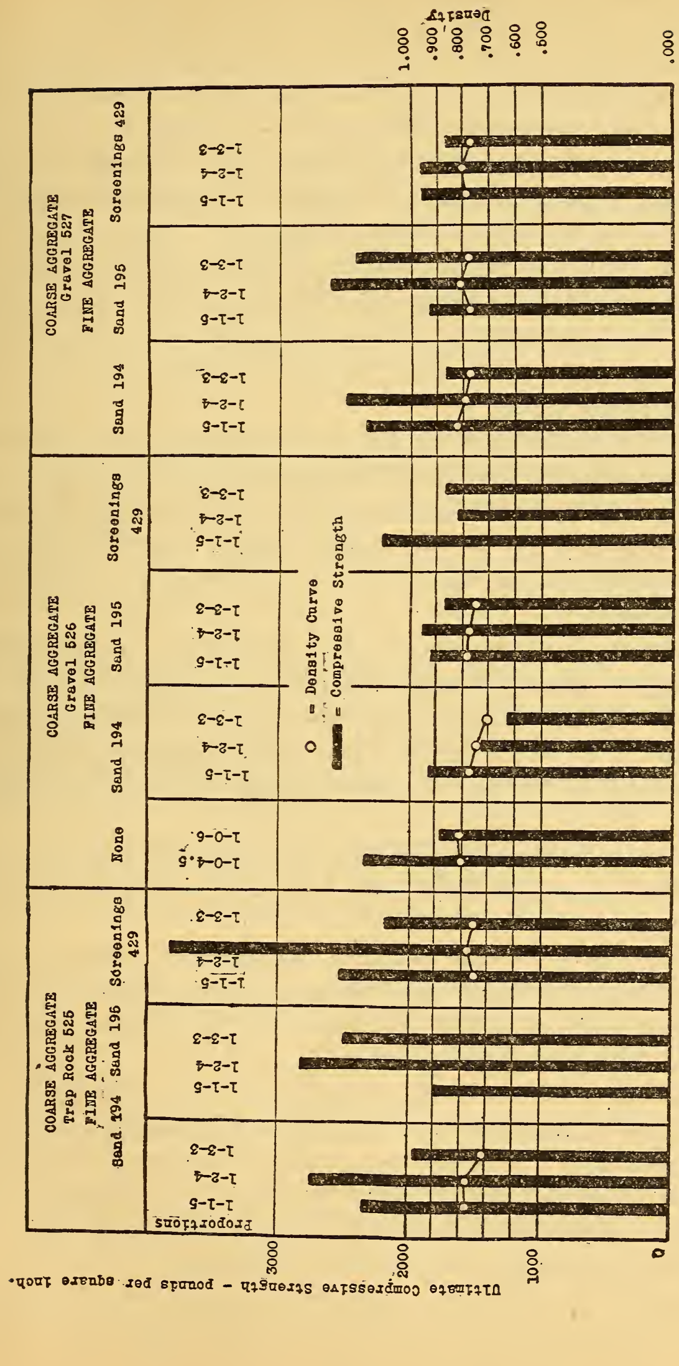

FIG. 29.—*Compressive strengths and "densities" of 1–9 concretes made with various aggregates. Proportions are in parts by volume. Age when tested, 90 days. Consistency, quaking. (Stored in air and sprinkled twice daily for the first 30 days. See table 26)*

gate, since the variation in shape of the particles as well as their gradation, hardness, and shearing strength will be a factor.

In Table 24 is included a series of density-yield-compressive strength tests made with stone 147 as coarse and fine aggregate in the form of 6-inch cubes. In the 1 : 9 proportion of total aggregate it is seen that maximum strength was attained by the 1 : 3 : 6 mixture, with a density of 0.814, while next in strength was the 1 : 2 : 7, with a density of 0.823. The 1 : 1 : 8 mixture, which had a density of 0.818, ranked third in strength. The density value of the 1 : 2 : 4 mixture can not well be compared with the above on account of the difference in quantity of cement used. Here, again, it is seen that a high strength is accompanied by a high density, although the maximum of one may not be associated with the maximum of the other.

The results of the tests of gravel concretes given in Tables 24 and 25 also indicate that there is a relation between density and strength and that a maximum density will insure a high compressive strength, although not necessarily the highest. In every case the lower strengths will be found among those mixtures having the lower densities.

Throughout all of the above tests it should be noted that in attempting to obtain the same apparent consistencies for all proportions it was necessary to vary the water percentages, and in some cases it is very possible that higher strengths might have been obtained by the use of slightly higher or lower percentages of water.

In Table 26 is given the results of a series of tests in which three coarse aggregates have been combined with three different fine aggregates.

These results show the relative compressive strength which may be obtained by combining several fine aggregates with the same coarse aggregate; also the results of the combination of the same sand with three aggregates.

In Table 26, series 2, 3, and 4, trap rock 525 is combined with the three fine aggregates sand 194, 195, and screenings 429 in the same proportions. In every case, considering the 1 :6 mixture, maximum strength was obtained in the 1 : 2 : 4 proportion, but minimum strength was attained in series 2 and 4 with the 1 : 3 : 3 mixture and in series 3 with the 1 : 1 : 5 mixture.

In series 5, 6, and 7 the three fine materials were combined with pit-run gravel 526, of which 38.5 per cent passed the ¼-inch screen. With the exception of the 1 : 1 : 5 proportion of series 5,

any addition of more fine material in the form of sand resulted in a lowered compressive strength, and it should also be noted that any such addition resulted in a lower density of the concrete.

The results throughout show that there is a direct relation between density and strength; the strength apparently varying directly as the density when the relative quantity of cement to sand is a constant. The compressive strength and density tests of Table 26 are shown diagrammatically in Figs. 26 to 29.

In Table 27 the effect on the compressive strength of the addition to the concrete of large amounts of coarse aggregate should be noted. Concrete composed of 1 part cement to 2 parts of trap screenings 429 and 4 parts gravel 527 was prepared and to this mixture was added large-size trap rock 524 in the proportions of 25, 50, 75, and 100 per cent of the volume of gravel used. The resulting mixtures then became 1:2:4:1, 1:2:4:2, 1:2:4:3, and 1:2:4:4, the last figure in each proportion representing the number of parts of trap rock 524 added. Expressed as cement, fine and coarse aggregate, the proportions by volume are, respectively, 1:2:5, 1:2:6, 1:2:7, and 1:2:8. In every case the addition of the large coarse aggregate resulted in a higher strength than was attained by the 1:2:4 gravel concrete.

Since the densities of these concretes were not determined it can not be stated which mixture was the densest, but it is very probable that all mixtures to which the stone 524 was added were denser than the 1:2:4 mixture. The additions of large stone probably resulted in a reduction of void space, in which case part of the cement which previously acted as void filler would be available for coating the surfaces of the added stone. The results of compression tests of Table 27 are shown diagrammatically in Fig. 30.

Since the mixture in which the ratio of cement to total aggregate was as 1:10 had as high a compressive strength as the 1:6 mixture it would seem that the density of the former must necessarily have been greater than that of the latter. These results suggest the possible economy of testing aggregates before using in work of magnitude.

It is of interest to note that in the case of every aggregate tested greater density was obtained with the mixtures in which the ratio of cement to total aggregate was as 1 to 9 than with the 1 to 6 mixtures, but the maximum strength was in every case obtained with the 1 to 6 mixtures.

(F) Quality as Affected by Method of Storage.—The normal method of storage of concrete, or normal conditions under which the process of hardening takes place, is exposure to the air, with occasional sprinkling in some cases, at early periods. Often the concrete in the interior of a building is allowed to harden without any treatment after the forms are removed and as a result the water which is required to insure maximum strength may be

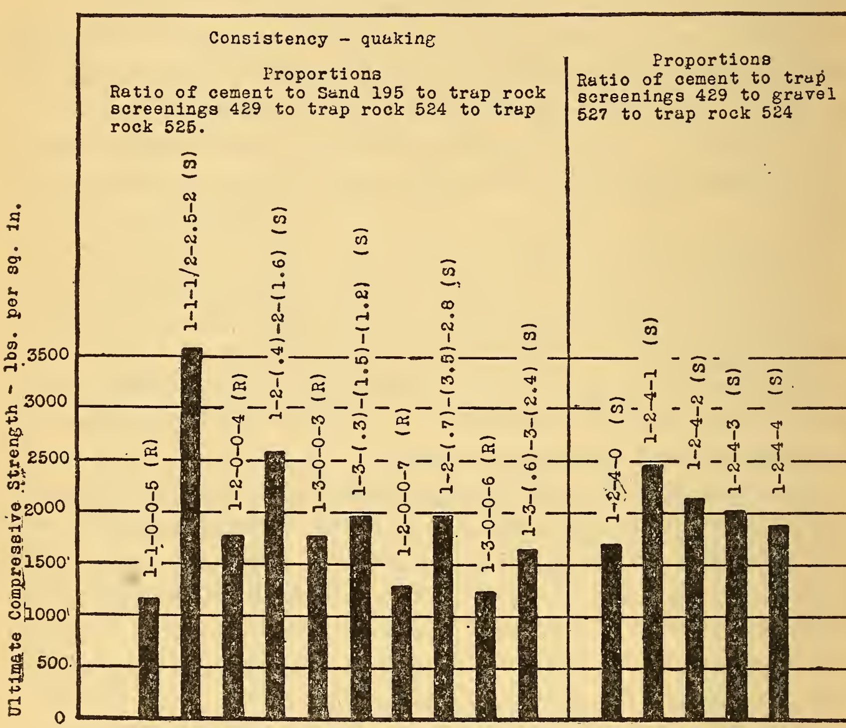

Fig. 30.—*Effect of size of aggregate on the compressive strength. Aggregate larger than normally used was added to concrete mixtures. Stored in air under cover. Sprinkled twice daily. Tested when 30 days' old. (Test pieces: S=14-inch cubes, R=8 by 16 inch cylinders. See Table 27)*

lost by evaporation. The rate of drying in structures, however, may be less than would usually be found in test specimens due to the larger masses of the concrete in the forms.

In Tables 19 and 28 are included the results of several series of tests in which the method of curing was varied.

In the case of the 1:2:4 proportion containing Jersey sand 187 and trap rock 505 (Table 19), one set of cylinders was immersed in water immediately after being deposited in the molds, a second was immersed in water after remaining 24 hours in the damp room,

and the third set was immersed in water after 8 weeks in the damp room. At all periods the specimens stored 24 hours before immersing were the strongest, followed by those immersed immediately after molding, while those stored for a long period in the damp room were the weakest.

Another parallel series was composed of 1 part cement to 6 parts pit-run gravel 503. One set of cylinders were stored in a damp room for the entire period, while the second were immersed in water after ageing four weeks in a damp room. Tests were made for periods up to one year. At all ages the test pieces stored in the damp room were the stronger, although the difference in strength was not great. Tests were made within a few hours after removal from the water or moist room, which accounts for the fact that the concrete immersed in water is the heaviest. It is possible that a higher strength might have been obtained in the case of the immersed specimens had they been allowed to dry before testing until in the same condition as those stored in moist air. It is interesting to note that the yield point and initial modulus of elasticity of the weaker concrete is slightly the greater.

The results given in Table 28 are especially interesting in that the test pieces were cured under conditions very similar to those to which concrete in ordinary building construction is exposed. One brand of cement, which met all the requirements of the United States Government specification, rather than a typical mixture of several brands, was used throughout.

Series 1, 2, and 3 of Table 28 made up of proportions 1:1½:3, 1:2:4, and 1:2½:5 were stored in the laboratory room and sprinkled daily for one week, after which they were exposed to changing conditions of atmospheric temperature and moisture. Series 4, a 1:2:4 mixture, was stored in a damp room for four weeks and sprinkled occasionally, then piled up out of doors and exposed to the weather.

A direct comparison can be made between series 2 and 4 at the ages of one and three months, since the same consistencies were used in both cases. The concrete stored in the moist atmosphere during the first four weeks exceeds the other in strength about 80 per cent at both periods. It should also be observed that the concrete of series 4 made under uniform conditions in the laboratory has a strength of only 1834 pounds per square inch at the end of four weeks, and that of series 2, stored under conditions common

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in building construction, shows a strength of only 1176 pounds per square inch. This would indicate that the factor of safety commonly used in the design of reinforced concrete under this condition, calculating on the basis of ultimate strength, may be nearer two than four, and under conditions of full calculated load the concrete may be stressed nearly to the yield point. Even the 1:1½:3 mixture of series 1 does not attain a strength of over 2000 pounds before the three-month period, so that the common assumption that a well-fabricated 1:2:4 concrete will have a compressive strength of 2000 pounds at the end of four weeks under normal field conditions can not always be considered a safe assumption.

The effect of difference in exposure during the early hardening period is further shown by the results of Table 29. Twelve test pieces were stored in a damp closet and 12 in the open air, exposed to the sun and wind. At 28 days the strength of the damp-closet specimens was approximately 25 per cent in excess of those stored in the open, although both exceeded the commonly assumed value of 2000 pounds per square inch.

The character of the exposure of concrete after molding materially affects its strength.

(G) Quality as Affected by Abnormal Methods of Curing.—The results of tests shown in Table 30 are of especial interest to manufacturers in the concrete-products industry, such as tile and block makers. In these industries the amount of floor and storage space can be greatly reduced by shortening the necessary time of curing. Briefly, the results show that up to 80 pounds per square inch gauge pressure steam has an accelerating action on the hardening of Portland cement mortar and that the compressive strength increases with the steam pressure as well as with the time of exposure to steam. A compressive strength considerably (in some cases over 100 per cent) in excess of that obtained normally after aging for six weeks may be obtained in two days by using steam under pressure for curing. Furthermore, the steam permanently accelerates the hardening of the concrete which subsequently increases in compressive strength with age upon exposure to the atmosphere. The tests above quoted, along with others which have been made, lead to the following conclusions in addition to the facts noted above:

The steam-cured mortar or concrete is of much more uniform appearance and is made lighter in color than normally aged mortar or concrete made from the same materials.

The mortar or concrete should obtain an initial set before it is exposed to the steam treatment.

For steam curing a "plastic" or "quaking" consistency is preferable to a very dry or very wet consistency.

The initial modulus of elasticity and the yield point of the mortar appear to increase directly with the duration of the steam treatment.

The initial modulus of elasticity and yield point appear to increase directly with the steam pressure.

The compressive strength obtained by steam curing is directly proportional to the cement content of the mortar.

The above tests were made on Portland cement mortars, but it has been found that the same conclusions apply to concretes. As an example a set of concrete cylinders was made up of 1 part Portland cement to 3 parts sand to 6 parts limestone. They were then placed in moist air for the first 24 hours, obtaining an initial set, after which they were exposed to a steam pressure of 80 pounds for 24 hours. They were tested directly after taking from the steam, being two days old, and had an average ultimate strength in compression of 2455 pounds per square inch.

As stated above, the combined action of the heat and moisture in the steam greatly accelerates the hardening process and causes the material to gain a strength at the end of two days which is in excess of that normally attained in four or six weeks.

(H) QUALITY AS AFFECTED BY THE CHARACTERISTICS OF THE AGGREGATE.—In making a study of any aggregate to determine its probable value as a constituent of concrere it is customary to make a number of tests of which probably the following are considered fundamental and are in most general use: (*a*) Weight per cubic foot; (*b*) density or percentage of voids; (*c*) gradation of particles (granular analysis).

(*a*) *Weight Per Cubic Foot.*—The weight per cubic foot of an aggregate depends upon a number of conditions, such as the specific gravity, the shape of the particles, the amount of moisture in the mass, the size and shape of the vessel used for this determination, and the manner or process used in filling the vessel. Because of these several variables it is difficult to check the determinations made in different laboratories unless some uniform procedure is followed. However, the results of Table 1 are directly comparable, since the method of making this determination was standardized.

The range of values shown varies from 90 to 120 pounds, being especially great among the bank-run gravels, while the weights of the granites appear unusually low. The results of tests given in the preceding tables show that the weight per cubic foot of the aggregate is no indication or measure, within the extreme ranges of values found in this investigation, of the quality of a material as a concrete aggregate, although it is necessary that this value be known for use in accurate proportioning.

(*b*) *Density*.—In Table 1 a comparison of the results of the void or density tests indicates that, for the materials tested, the amount of voids was greater in the limestones than in the gravels in most cases. The relative amount of void space apparently bears little relation to the resulting strength, a number of aggregates with high precentages of voids showing very good results in the strength tests. Since it is the function of the sand to fill the voids in the coarse aggregate, a high or low percentage of voids has no direct connection with the strength of the resulting concrete, but it would appear that the quantity of sand required would necessarily vary with the void space. However, since an increase in the number of particles in a given volume is accompanied by increased surface area which must be coated with cement, coarse aggregate having the smaller void space might be preferred, with all other conditions equal.

Since the void space of the individual particles of most coarse aggregates as compared with the mortars in which they are used may be considered as zero and the density of these individual particles as compared with the density of the mortar may be considered as 1.00, the density of the concrete obtained by mixing the coarse aggregate with the mortar will be greatest when the maximum quantity of aggregate is used, which will not have interspace in the compacted form greater than the total volume of mortar.

For example, if we have 1 cubic foot of mortar similar to the mortar obtained with sand 172, Table 4 in the 1 to 3 mixture, whose density is 0.676, and replace 60 per cent of the volume of mortar in the cubic foot with coarse aggregate which has practically no voids in the individual particles in which the mortar can enter or, in other words, the aggregate has a density of 1.00, the resulting concrete would have a density of $0.40 \times 0.676 + 0.60 \times 1.00 = 0.870$.

This, of course, is equivalent to replacing 0.6 of a cubic foot of the mortar with one solid block of stone of equal volume. It

probably would not be possible to combine a mortar and a coarse aggregate in such a way as to have the stone particles lie as closely together in the resulting concrete as they did in a loose or compacted pile before being mixed in the concrete, and therefore the quantity of mortar required must always be greater than the actual void space in a compacted volume of the stone aggregate. Furthermore, there will probably be some interspace between the coarse aggregate and the mortar which will decrease the density, and therefore the larger the particles of coarse aggregate, assuming that they are as well graded, the greater will be the density of the concrete in which they are used.

(*c*) *Gradation of Size of Particles.*—The results given in Table 14 show the effect of the combination of the coarse aggregates with different sands in various proportions. In every case the proportion of cement to the combined fine and coarse aggregates was as 1 to 6 and 1 to 9.

The crusher-run material of stone 388, without the addition of sand, attained a strength at the end of four weeks of 2503 pounds per square inch in the 1:0:6 mixture. In the 1:½:5½ mixture, using sand 184, the strength obtained was 2275 pounds, with sand 185, 2248 pounds, practically the same values. In the 1:1:5 mixture, using sand 184, an increase in the proportion of fine material causes an increase in strength to 2530 pounds, while sand 185 shows a decrease to 1987 pounds. Further increases in proportion of fine sand are accompanied with corresponding decreased strengths. The addition of any fine material seemed to lower the strength with the exception of sand 184, whose strength value in the 1:1:5 mixture was about the same as that of the 1:0:6 mixture.

Considering the 1:9 proportions, the maximum strength is obtained with both sands in the 1:1:8 mixture, and any further increase of fine material lowers the crushing strength.

Stone 251 in the proportion of 1 part cement to 6 parts of total aggregate, using sand 183, obtained maximum strength in the 1:2:4 mixture, while by using fine material from the same aggregate as a sand the greatest strength was given by the 1:1:5 mixture, but this value was nearly 800 pounds lower than that obtained with sand 183. In the proportion of 1 part cement to 9 parts of total aggregate, sand 183 in a mixture of 1:2:7 had a compressive strength of 1538 pounds per square inch, while with screenings of stone 251 in a 1:1½:7½ mixture it had a compressive strength of 1663 pounds per square inch.

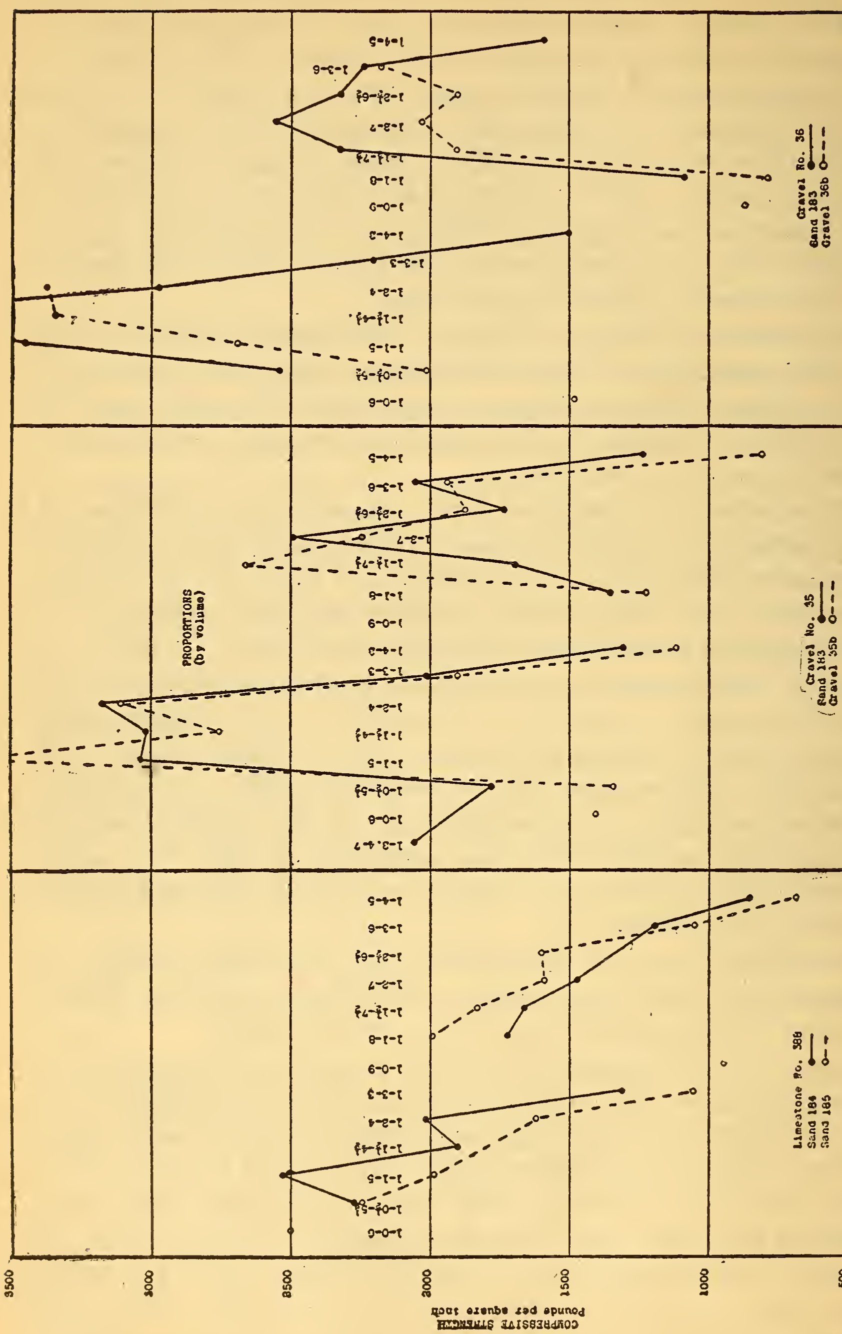

FIG. 31.—*Relation of proportion of mixture to the compressive strength of concrete for three aggregates, each combined with the same two sands. Age, 4 weeks. (Test pieces, 6-inch cubes. See Table 15)*

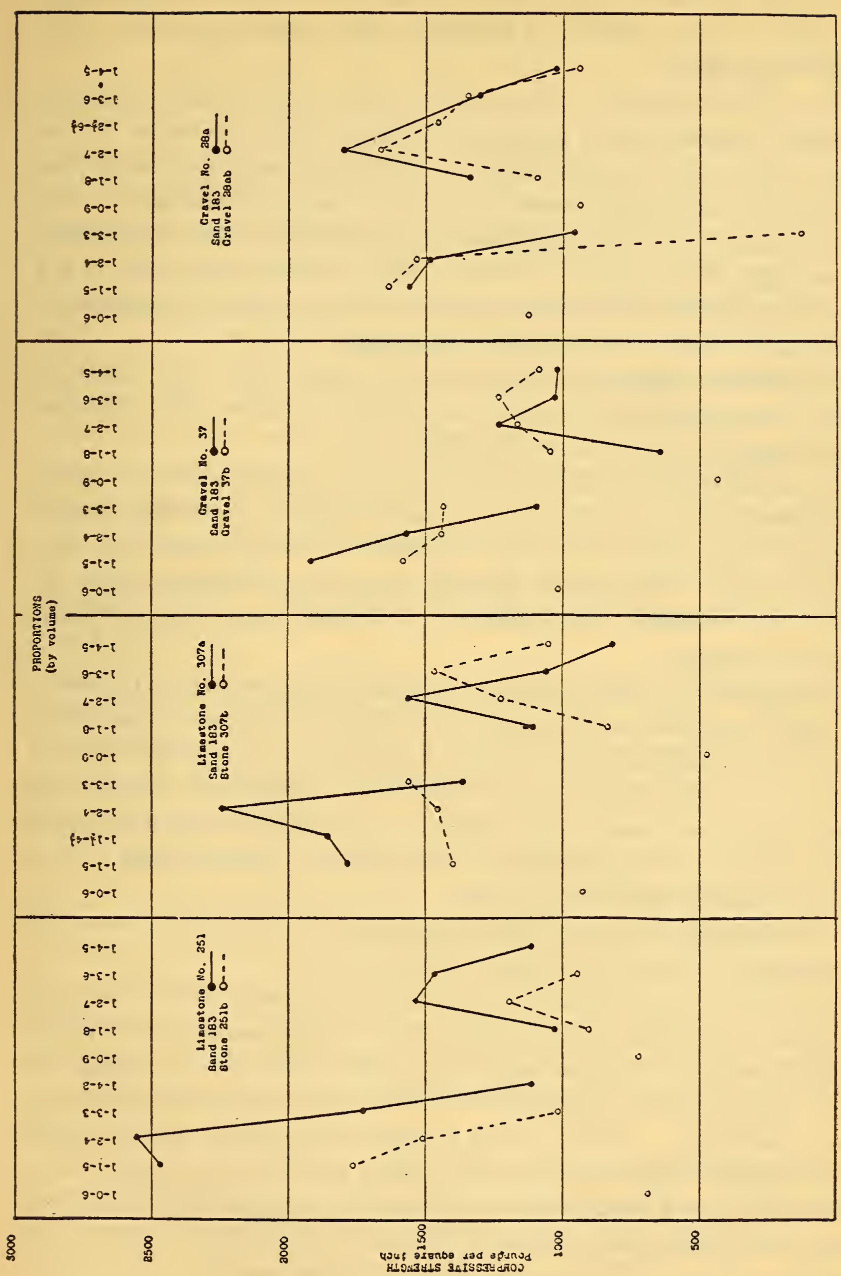

FIG. 32.—*Relation of proportion of mixture to the compressive strength of concrete for four aggregates, each combined with the same two sands. Age, 4 weeks. (Test pieces, 6-inch cubes. See Table 15)*

The above variable results are also obtained with the gravel concretes; different sands were required in different proportions in order to give maximum strength when mixed with the same coarse aggregate.

The values obtained with gravel 36 and sand 55 and additional screened material from gravel 36 illustrate that the value of two sands can not be determined by arbitrarily assuming some one proportion and using those results as a basis for selection. The results from the 1:2:4 proportion might indicate that the natural screenings were superior to sand 183, but the proportion 1:1:5 gives the highest strength of all for sand 183 and a considerably decreased value for the natural screenings.

The effect of gradation of size of particles is even more marked when the same sand is considered in combination with different coarse aggregates, as shown by Table 31.

In these results of tests of limestone aggregates, stone 210 gave the lowest value in the 1:2:4 mixture while it gave the second highest when used in the 1:3:6 mixture. Stone 210 showed only about 20 per cent greater strength in the 1:2:4 mixture than in the 1:3:6 mixture while stone 150 showed over 150 per cent greater strength.

Limestone 150 and gravel 35 both gave high results and a study of their granular analyses given in Table 1*a* indicates that limestone 150 contained as much fine material as any of that type of aggregate, while gravel 35 was one of the coarsest of the gravels. Such results as these would indicate that strength does not bear a direct relation to gradation of the particles, independent of the other characteristics of the stone.

The strength of some of these aggregates when mixed in various proportions is shown in Figs. 31 and 32.

In Table 31*a* are shown the results of compression tests on concrete made with the same crushed rock and two sands, one of which would probably be condemned by visual inspection as being too fine, 41.6 per cent passing the No. 48 sieve, and too one-sized to be satisfactory. At the age of 9 days the concrete made of sand 200 is slightly stronger than that made with the beach sand 201, but at the age of 30 days the conditions are reversed, both concretes being well above the commonly assumed standard of 2000 pounds per square inch. The results of the granular analysis of the stone, trap rock 508, show that it contained very little fine material, which at least partially explains the high results obtained with the beach sand 201. Such results as these are only further evidence

that the visual inspection of a sand is unreliable, and that the only certain criterion of quality is to combine and test the sand with the coarse aggregate in the desired proportions.

The value of chats, zinc mine tailings, as a concrete aggregate is shown in Tables 31*b* and 31*c*.

The results shown in Table 31*b* represent tests of material received from Mascot, Knox County, Tenn. The results show that the "run-of-mine" product lacks sufficient fine material to produce a dense, workable concrete, although the strength is practically the same as is obtained for stone or gravel concretes. By screening out a portion of the fine material and then recombining with run-of-mine material a good quality concrete is obtained.

The results of tests on material received from a mine at Webb City, Mo., are shown in Table 31*c*. The strength compares favorably with those ordinarily found for concretes made of usual commercial aggregates. The values obtained, as for the preceding series, show that run-of-mine chats are lacking in fine material, and that regrading is necessary to produce a concrete which can be placed in a dense mass, or that it is necessary to increase the quantity of fine material by the addition of particles smaller than one-fourth inch.

Based upon the tests which are included in the two tables, it can be stated that chats are suitable for use in concrete, although it may be necessary to screen and recombine the aggregate to obtain a workable dense mixture, depending upon the characteristics of the particular material.

The granular analyses of a number of the concretes used in the cube tests are shown in Figs. 33 to 36. The so-called curve of maximum density is included for comparison. It is possible that a separation of the aggregate in various sizes and recombining so as to more nearly approach these curves would have resulted in concretes of greater strength than are shown in these tests, but it must be admitted that some very strong concrete was produced in which there is little similarity between the so-called theoretical and actual granular curves.

In Figs. 37 to 39 are shown the granular analysis curves of several of the concretes included in Tables 26 and 27. The results of density and compressive strength tests are included for comparison.

It will be observed that in some cases, as in Fig. 39, with a number of combinations of the same aggregates the mixture giving the maximum strength has a granular analysis curve differ-

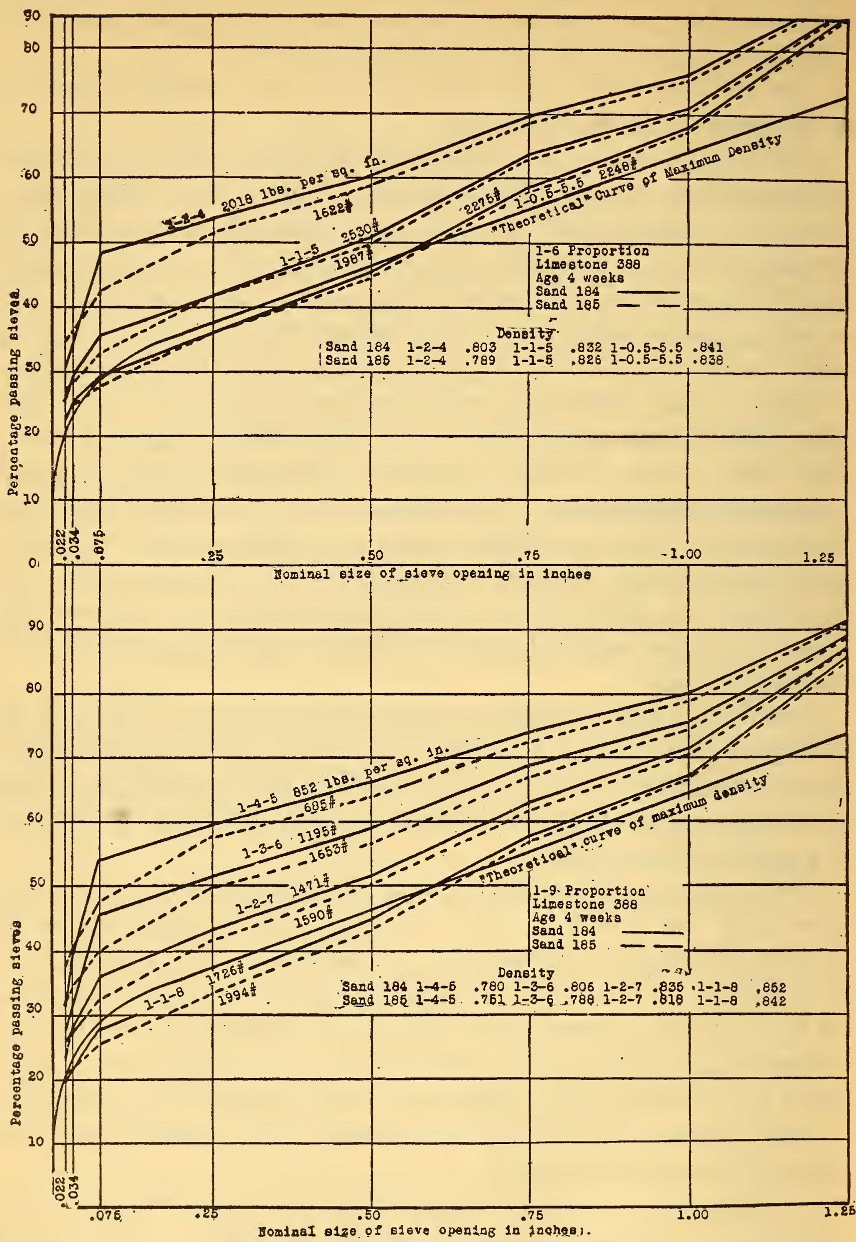

FIG. 33.—*Relation of granular analysis and compressive strength to Fuller's "theoretical curve of maximum density."* (*Test pieces ,6-inch cubes. See Tables 1, 1a, and 15*)

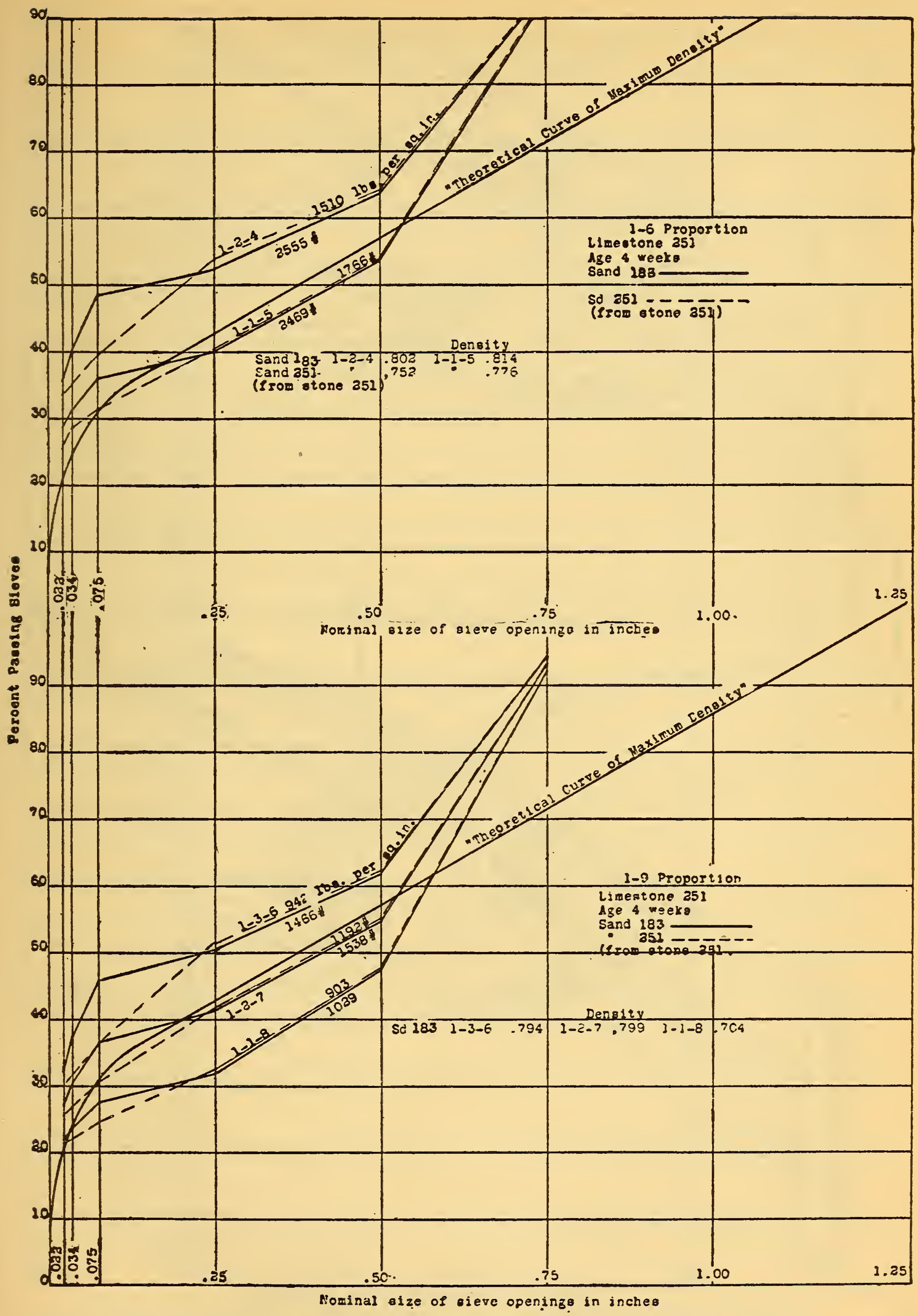

FIG. 34.—*Relation of granular analysis and compressive strength of concrete to Fuller's "theoretical curve of maximum density."* (*Test pieces, 6-inch cubes. See Tables 1, 1a, and 15*)

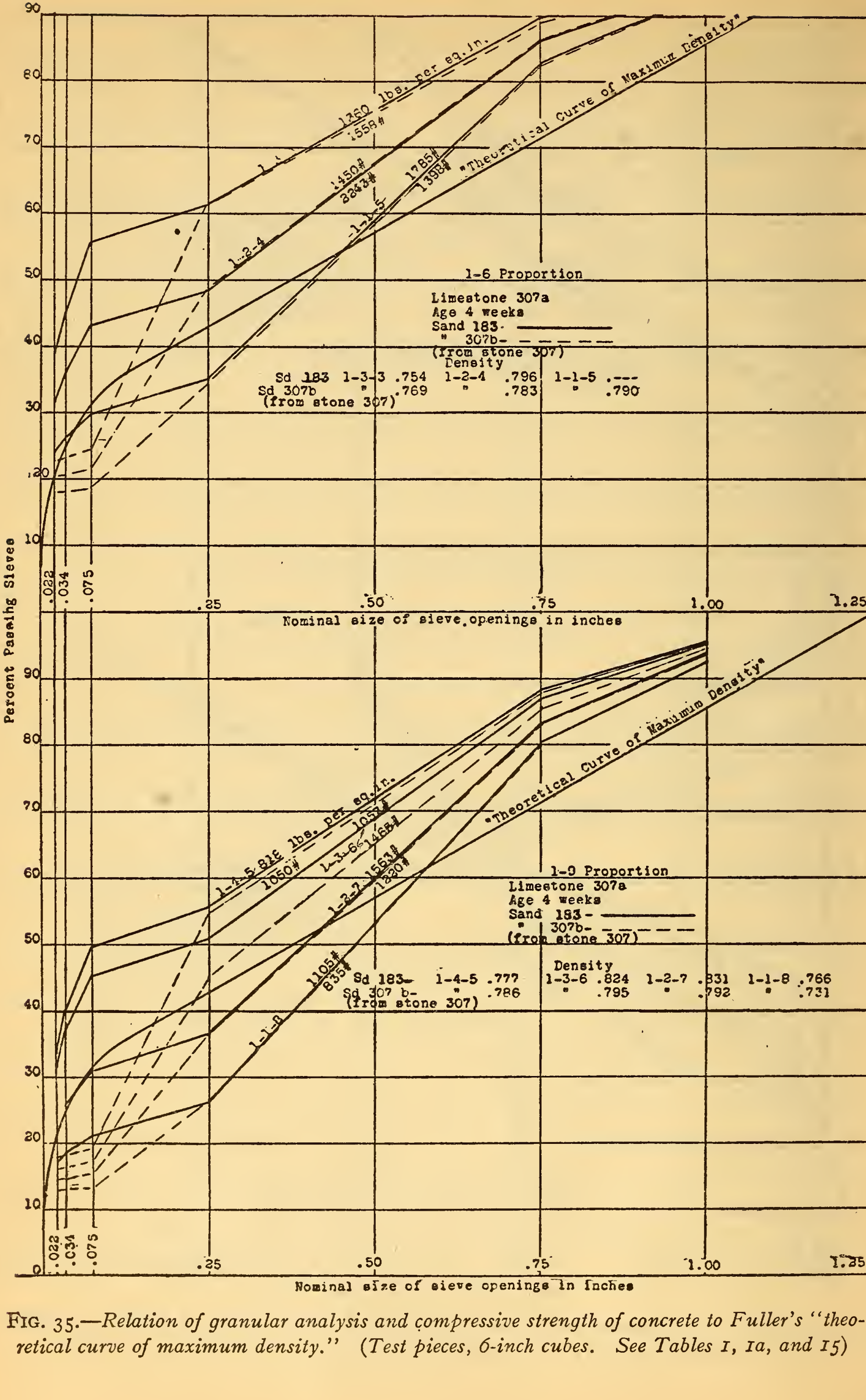

FIG. 35.—*Relation of granular analysis and compressive strength of concrete to Fuller's "theoretical curve of maximum density."* (*Test pieces, 6-inch cubes. See Tables 1, 1a, and 15*)

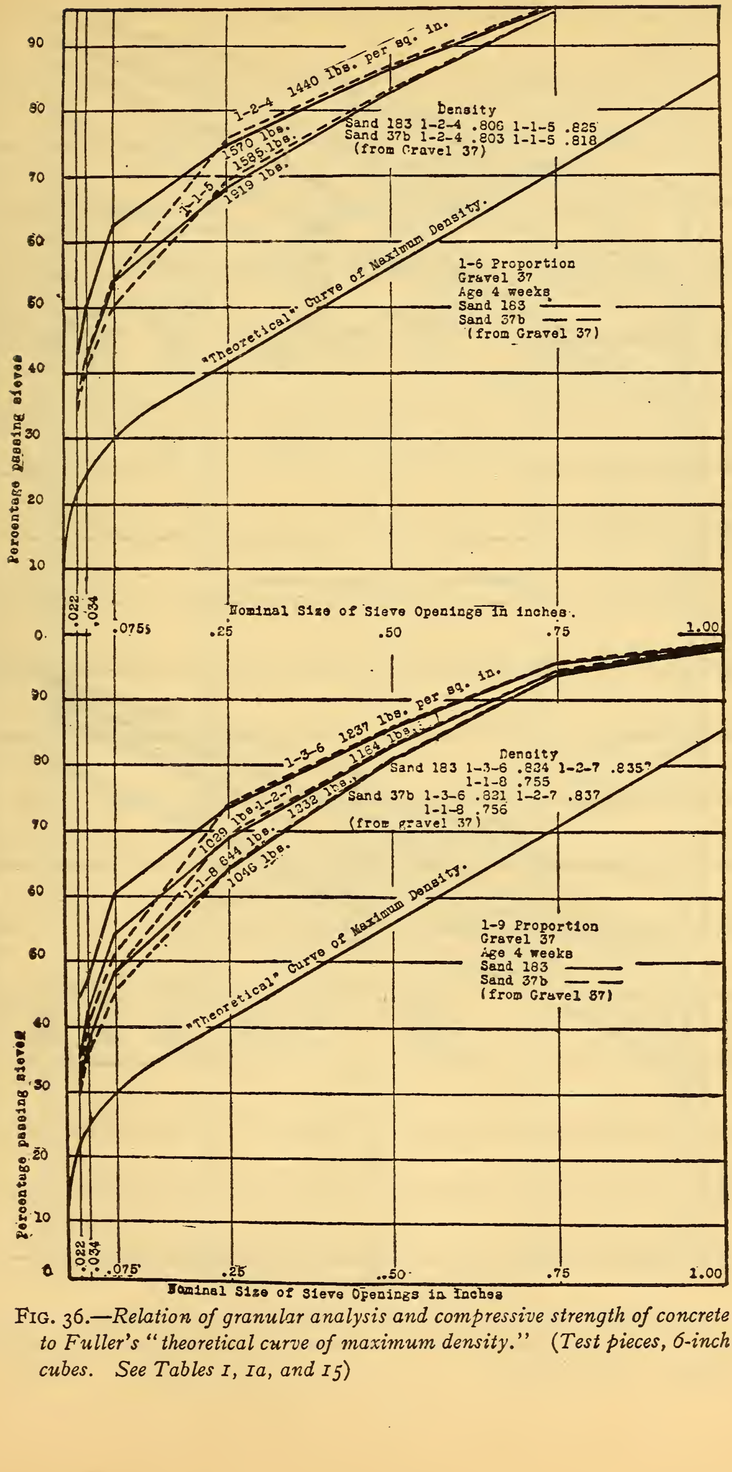

FIG. 36.—*Relation of granular analysis and compressive strength of concrete to Fuller's "theoretical curve of maximum density."* (*Test pieces, 6-inch cubes. See Tables 1, 1a, and 15*)

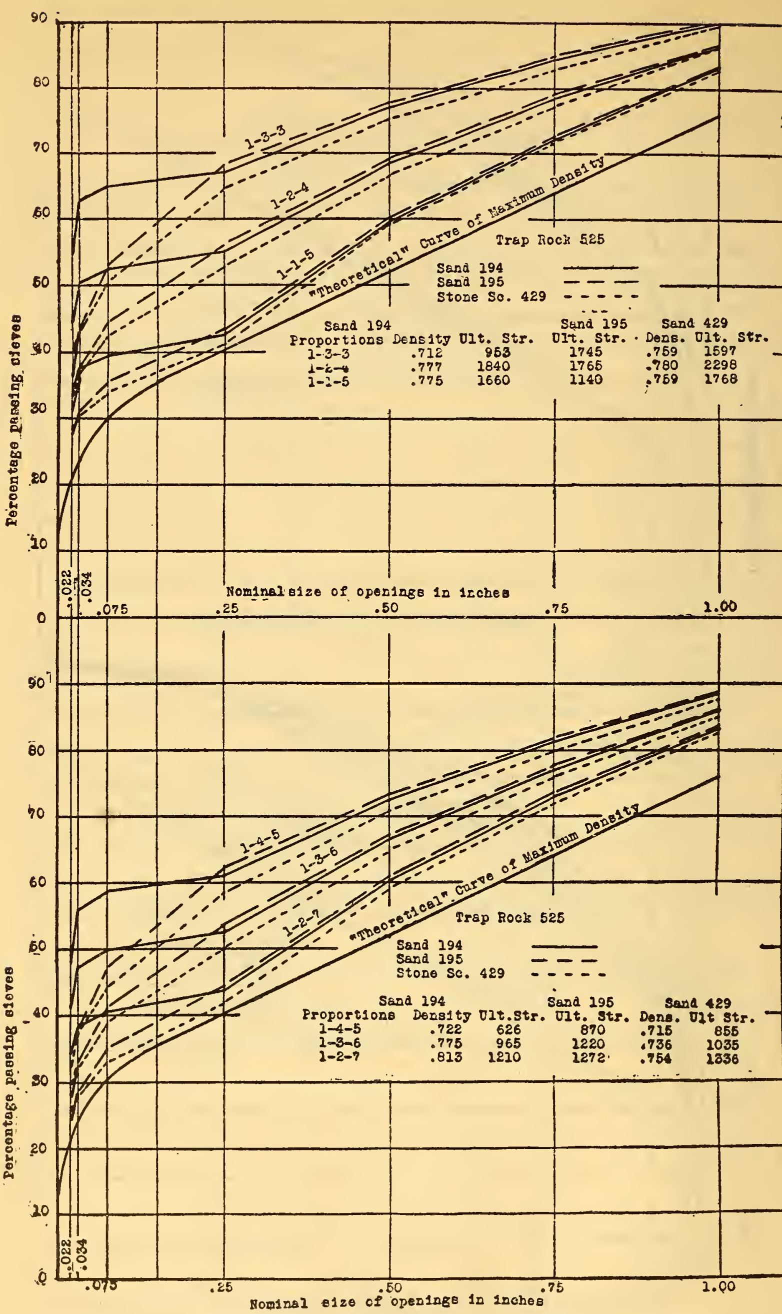

FIG. 37.—*Relation of granular analysis and compressive strength of concrete to Fuller's "theoretical curve of maximum density."* (*Test pieces, 8 by 16 inch cylinders. See Table 26*)

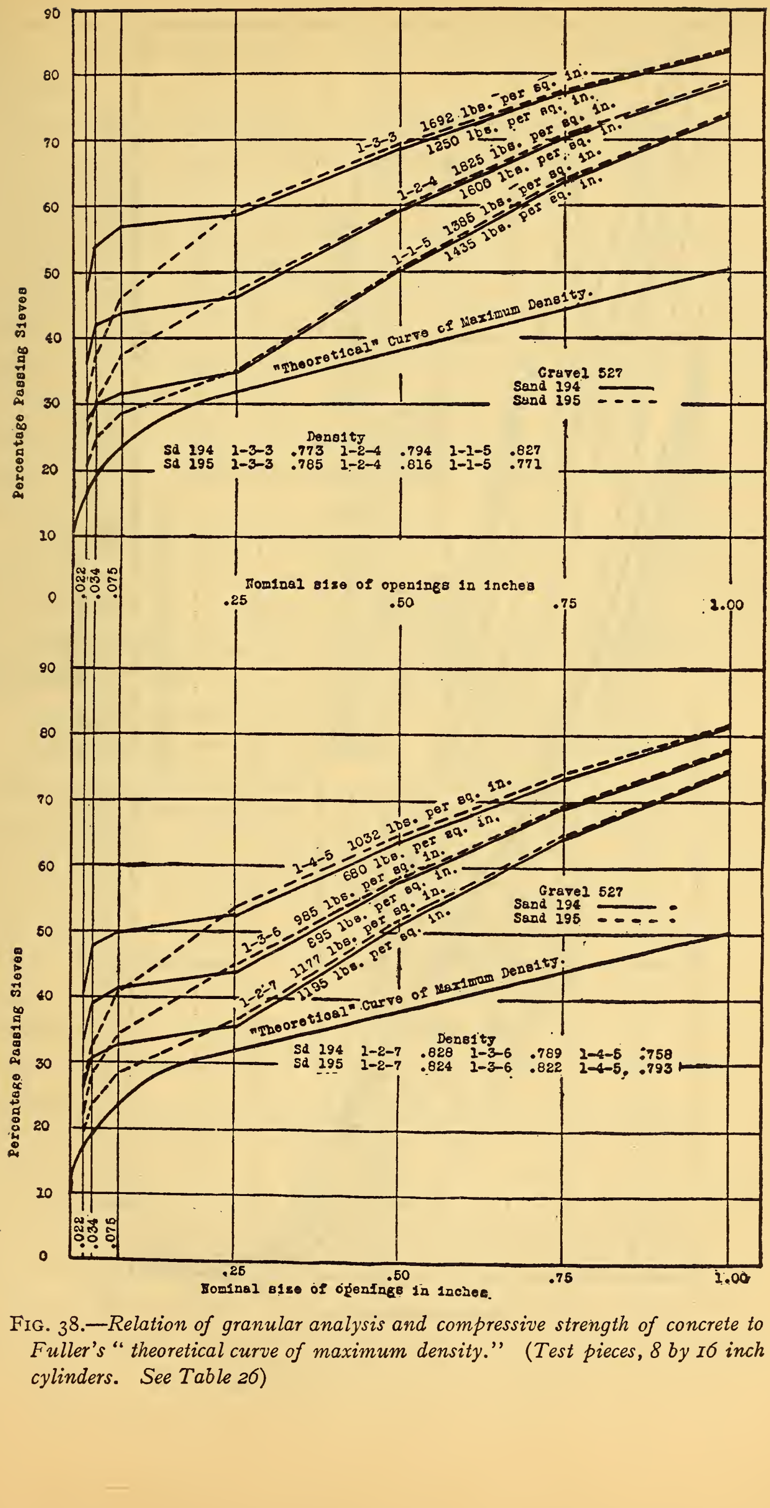

FIG. 38.—*Relation of granular analysis and compressive strength of concrete to Fuller's "theoretical curve of maximum density." (Test pieces, 8 by 16 inch cylinders. See Table 26)*

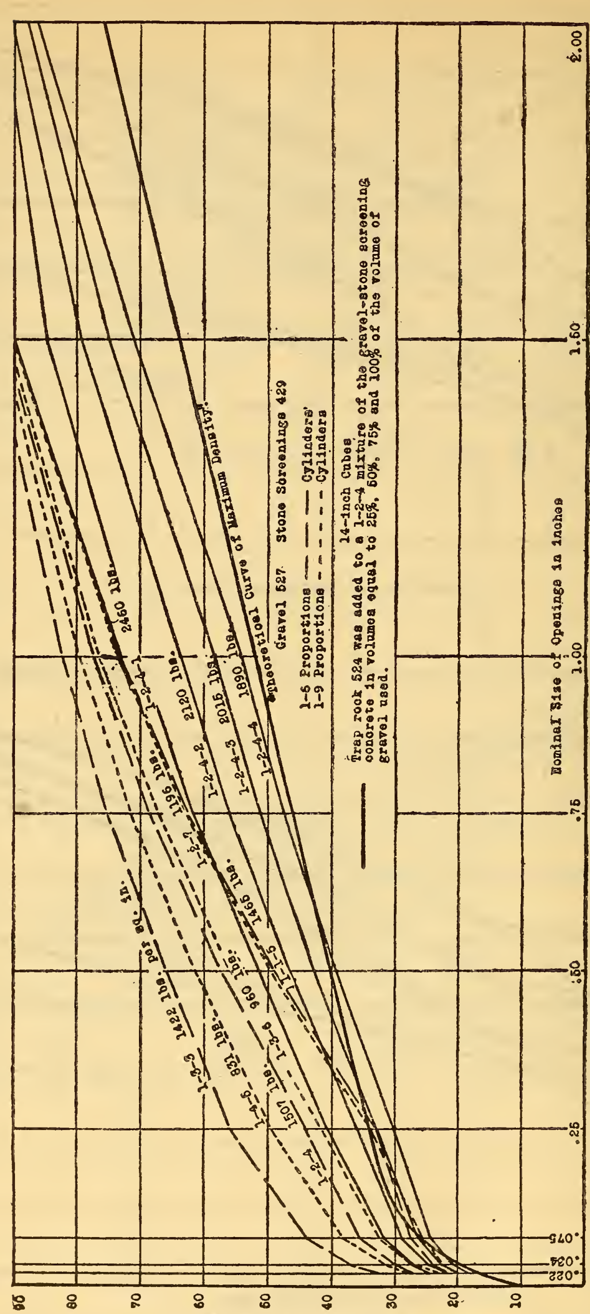

Fig. 39.—*Relation of granular analysis and compressive strength of concrete to Fuller's "theoretical curve of maximum density." (Test pieces, 8 by 16 inch cylinders and 14-inch cubes. See Table 27)*

ing most widely from Fuller's theoretical curve. No single curve can be selected which represents a combination giving maximum density and strength for all the materials included in these diagrams.

The results of a number of tests in which one material was combined in various ways and in several proportions with cement are given in Table 32.

Unfortunately the granular analysis of the aggregate is not available, but it is of interest to note that the pit-run material had practically as high a strength as any of the combinations. Referring to results of tests in Table 14, 1:2:4 proportion of aggregate 307 with sand 183, and Table 19, 1:2:4 proportion of aggregate 505 with sand 188, they both have approximately the same strength, although in the case of one of the mixtures 40 per cent passed the No. 50 sieve and of the other only 20 per cent passed this sieve.

A further illustration of the use of a very fine sand which gives satisfactory results in a concrete is shown by the following, in which sand 202 is combined with gravel 504, in a 1:2:4 concrete and tested at the ages of 7 and 28 days. Each result is the average of tests of two 8 by 16 inch cylinders.

Age 7 days, ultimate compressive stress 1390 pounds per square inch.
Age 28 days, ultimate compressive stress 1994 pounds per square inch.

One of the most elaborate theories advanced for the scientific proportioning of concrete to obtain maximum strength is based upon the results of an investigation in which a number of aggregates were separated into different sizes and recombined in various proportions. The fine and coarse aggregate are screened into various sizes, the more the better, and then recombined in such a manner that the granular analysis of the resulting concrete will give results which, when plotted, will closely fit a curve, a combination of ellipse and straight line, called by the authors, Fuller and Thompson, the curve of maximum density and strength.[5] The so-called theoretical curve used in this process may be correct for the aggregates used in the experiments. The principles may apply to other materials if graded as recommended, but sufficient data are not included in the authors' paper to make this empirical curve of general application.

Materials are seldom found in nature combined so as to have a gradation similar to that recommended, and a study of the results

[5] Trans. of A. S. of C. E., March, 1907, p. 222.

included in this paper does not show that materials having a gradation approaching this curve are in any way preferable. The many results reported in this paper would tend to disprove the authors' contention that the maximum density for any aggregate has a gradation which when plotted approaches the curve they suggest, regardless of shape of particles. For example, if we consider an exaggerated case and assume a coarse aggregate of exact cubical form and uniform size, the maximum density would be obtained if this were combined with just sufficient cement to coat the surfaces and bind them together without any material of intermediate size. The finer and more uniform this cementing material is in size the greater the density of such a mixture. For mixtures of cubical or angular materials of various sizes and gradations the maximum density will depend upon the relative shape of the particles of each size, as well as other factors. It is generally recognized in practice that gravel concretes flow into place with more ease than stone concretes, which is probably due to the shape of the particles.

Maximum density is obtained when the particles lie as close together as is possible, which depends upon the shape of particles, relative shape of particles of various sizes, the proportionate quantity of each size, the readiness with which the materials compact, the method of mixing, the quantity of water used in mixing, the method employed in placing in forms, etc. Therefore every aggregate or combination of aggregates will have its own maximum density curve and no one curve can be used for combining dissimilar materials even of the same type. This statement is verified by the many tests included in this paper as well as by the results obtained by other investigators.

(I) Quality as Affected by the Proportions of Cement to Aggregate.—A study of any of the groups of tests included in the preceding tables shows that there is a definite relation between the compressive strength and the proportion of cement to total aggregate. The strength varies in the same manner, although not in the same proportion, as the cement content in the mixture. This relation only holds true for any one combination of coarse and fine aggregate, and any change in gradation of total aggregate may affect the strength so as to neutralize the effect of change in the cement content.

In Table 33 are given the results of tests of two aggregates, gravel and limestone, in which the proportions of fine and coarse aggre-

gate remain constant and the cement content varies from 33.3 per cent to 8.3 per cent of the total aggregate. The compressive strength yield point, modulus of elasticity, and weight per cubic foot all increase directly with the increase in content of cement. In Table 34 are given the relative strengths of a number of aggregates in various proportions, which further show that the compressive strength is increased as the relative quantity of cement is increased in any one combination of aggregates. These results also show that with the proportion of cement fixed the compressive strength may be increased or decreased by varying the relative proportions of fine and coarse aggregate. The correct proportions for maximum strength can only be determined by trial.

Table 35 contains the weight per cubic foot of several concretes, showing the effect of variation in the consistency, variation in the ratio of cement to the same total aggregate, and the relation of density and weight per cubic foot for different proportions of the same materials. The results in this table show that the quaking consistency gives a heavier concrete than the mushy or fluid consistencies. The weight per cubic foot of concrete decreases directly as the proportion of cement to the same total aggregate decreases.

The lower group of results show that the weight per cubic foot of concrete does not bear a direct relation to the density when the relative proportions of fine and coarse particles are varied, even though the proportion of cement to total aggregate is the same. The results with stone 388 and sand 185 appear to show a definite relation between density and weight per cubic foot, but reference to Table 1 will show that this is due to the low specific gravity and weight per cubic foot of sand 185.

(J) Quality as Affected by the Age of Concrete.—Many of the preceding tables contain results of tests of the same concretes at various ages extending up to one and in some cases two years.

With very few exceptions there is a direct increase in strength of all concretes with age. The rates of increase depend upon a number of factors, such as the rate of hardening of the cement, the consistency of the mix, method of mixing and molding, curing, character of aggregate, etc., and therefore no general equation can be written to express the rate of increase in strength, as it will vary for every batch of concrete in which the above factors vary.

Tables 36 to 38 contain the results of tests of concrete at various ages, with several different aggregates. The results given

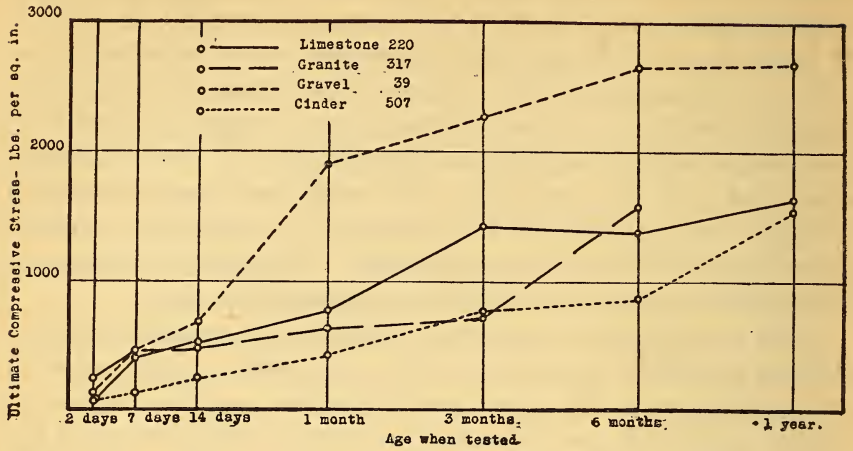

FIG. 40.—*Variation of yield point in compression with age of 1–2–4 concretes made with limestone, gravel, granite, and cinder aggregates with the same sand. (Test pieces, 8 by 16 inch cylinders. See Tables 8 and 36)*

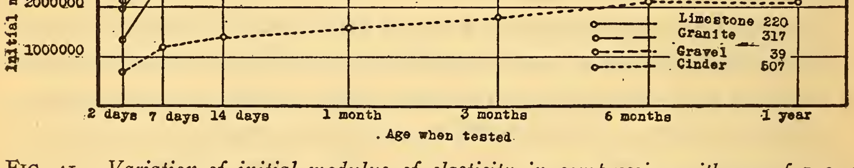

FIG. 41.—*Variation of initial modulus of elasticity in compression with age of 1–2–4 concretes made with limestone, granite, gravel, and cinder aggregates with the same sand. (Test pieces, 8 by 16 inch cylinders. See Tables 8 and 36)*

in Table 36 show a progressive increase in compressive strength from 2 days to 14 days. In every case at 7 days the compressive strength is in excess of 700 pounds, but the yield point is only 140 pounds in the case of cinder concrete, and slightly above 400 pounds for the other aggregates. Figs. 40 to 42 show the

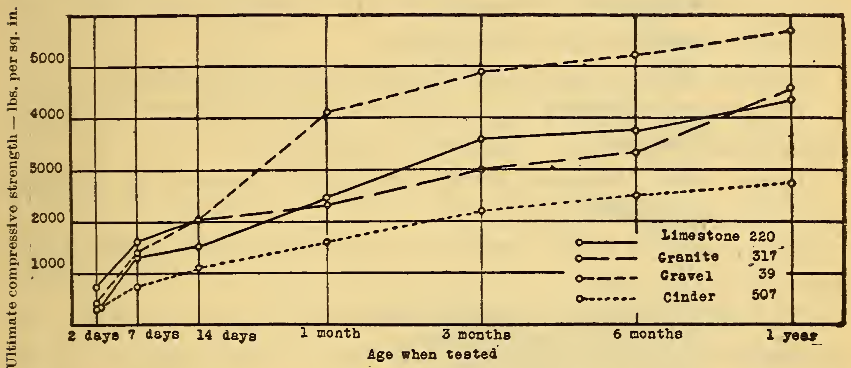

FIG. 42.—*Variation of ultimate compressive strength with age of 1–2–4 concretes made with limestone, granite, gravel, and cinder aggregates with the same sand.* (*Test pieces, 8 by 16 inch cylinders. See Tables 8 and 36*)

relation of compressive strength, yield point, and modulus of elasticity to age for periods ranging from two days to two years. These curves show in a general way the rate of increase in strength with age for mixtures similar to those included in the test, but they should not be considered representative of all mixtures or for all materials.

VI. SUMMARY

1. PORTLAND CEMENT MORTAR MIXTURES

Sands as a type of fine aggregate can not be said to be superior to limestone screenings.

The proper gradation of the fine aggregate for maximum strength in a mortar appears to vary for different materials.

The results of the tests of the mortars included in this paper would indicate that for most materials the highest strengths are obtained with those having a gradation of particles approaching a straight line. There are materials, however, which have a gradation varying widely from a straight line which give high strength in mortars.

The quality of a sand can not be judged from its gradation alone. Any limitation arbitrarily placed upon the proportions of

the particles of various sizes will probably eliminate some very satisfactory materials.

No fine aggregate should be rejected because of its "silt" content determined by washing or assuming the material passing the No. 200 sieve as silt, as it may be advantageous even in relatively large quantities or detrimental in small quantities depending upon its form, character, and distribution.

Mortars having high density usually have high strength.

The quality of sands to be used in cement mortars can not be determined from their "uniformity coefficients."

There is no difference in the strength developed by rounded and sharp-grained sands.

The quality of sands can not be determined from their specific gravity and porosity.

The only satisfactory method of determining the value of a fine aggregate in mortar mixtures is to test it in the mixture in the proportion to be used, exposed to the same conditions as in the proposed structure.

Common usage has demonstrated that certain sands are satisfactory and therefore no tests of these materials are necessary excepting to identify them.

The relative value of several fine aggregates to be used in concrete can not be determined by testing them in mortar mixtures. They must be tested in the combined state with the coarse aggregate.

Several curves are given in Fig. 43 showing the general effect on the compressive strength of variation of one of the factors in the process of fabrication of mortars. The diagrams are intended to show the general effect, and the values given should not be interpreted as showing a positive relation for any specific aggregate or mixture.

In practice the variation might be greater or less than that shown in the curves, depending upon specific conditions and materials.

2. PORTLAND CEMENT CONCRETE MIXTURES

The general effect on the compressive strength of variation of the several factors entering into the fabrication of concrete is shown graphically in Fig. 44. The diagrams are intended to show the trend or general effect of each factor concerned in the fabrication of concrete in a similar manner to those of Fig. 43, and

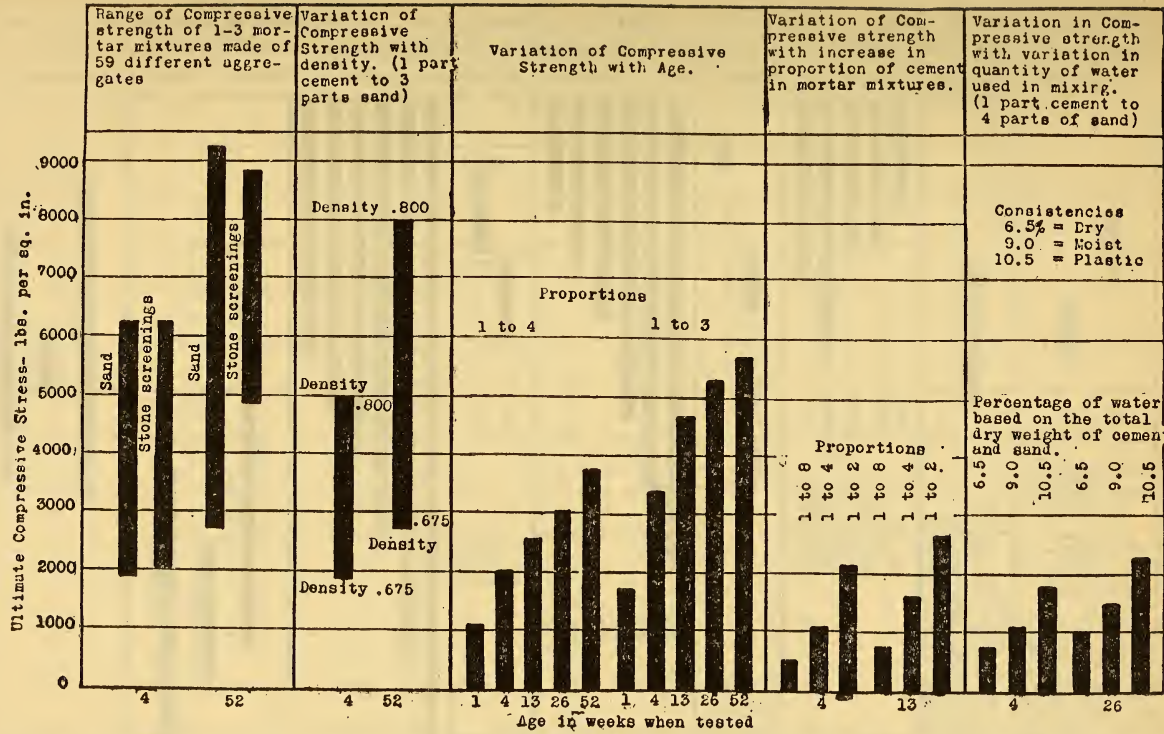

FIG. 43.—*Summation diagrams showing the range in compressive strength of Portland cement mortar mixtures which may be obtained under various conditions. These diagrams are intended to show the general effect on the compressive strength of the variation of one factor in the process of manufacture as taken from the results included in this paper. The ranges shown should not be considered as the maximum obtainable in practice*

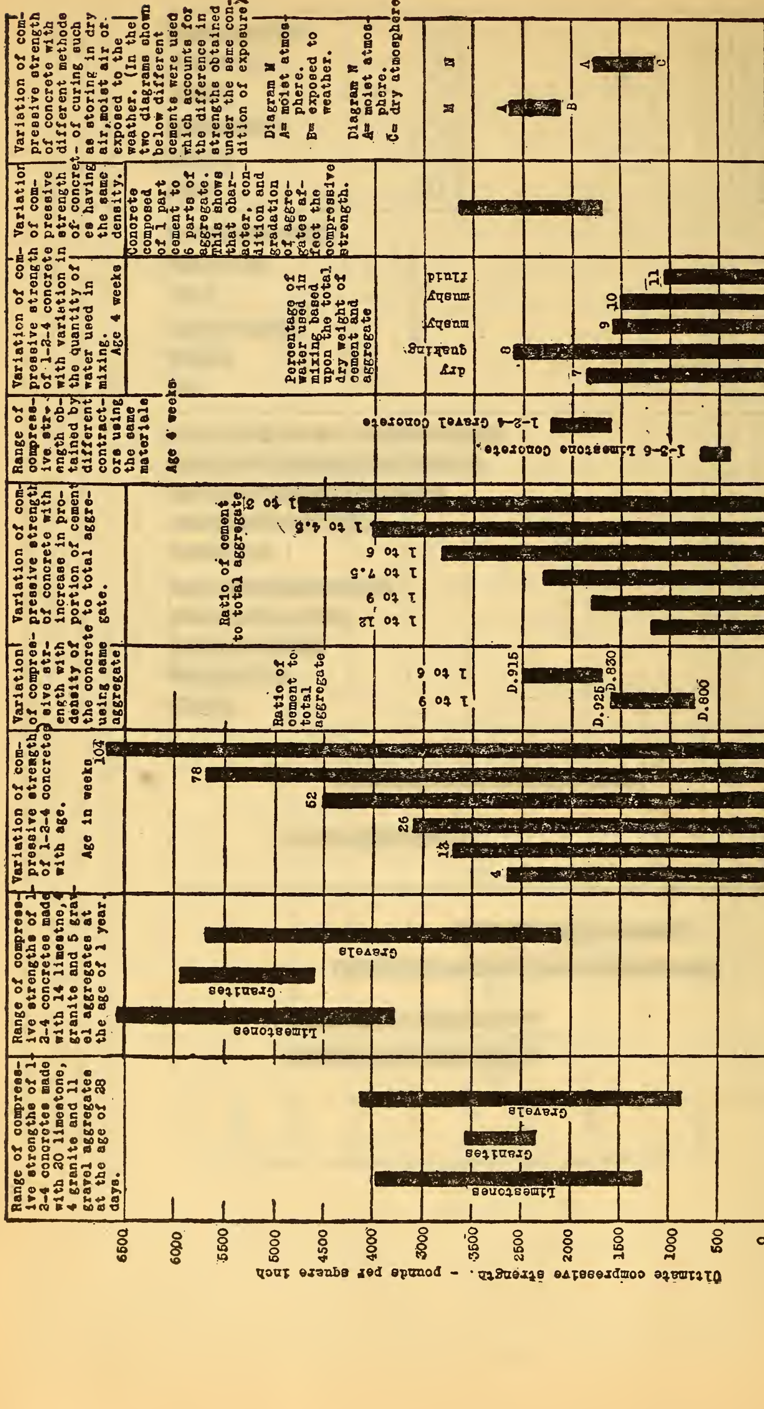

FIG. 44.—*Summation diagrams showing the range in compressive strength of Portland cement concretes which may be obtained under various conditions. These diagrams are intended to show the general effect on compressive strength of the variation of one factor in the process of manufacture as taken from the results included in this paper. The ranges shown should not be considered as the maximum obtainable in practice*

the values given should not be interpreted as showing positive relations applicable to all materials and conditions.

(A) Relation of Type of Aggregate to Compressive Strength.—No type of gravel or stone aggregate can be said to be generally superior to any other type used as coarse aggregate in concrete mixtures. Certain limestones are superior to certain gravels, and some gravels are better than other limestones. The range of qualities in any of these types is very great and the strengths of concretes made up of several different materials of the same type may vary as much as several hundred per cent with all other controllable factors uniform.

(B) Relation of Workmanship to Compressive Strength.—Undoubtedly greater uniformity is generally obtained by machine mixing than by hand mixing. The method of mixing is of little importance so long as it results in a homogeneous mass. Using proper methods and with the expenditure of sufficient labor, results indicate that as good concrete can be obtained by hand mixing as by machine mixing, although it probably would not be economical.

With all other factors constant the results included in this paper show that differences in manipulation of the mixture by the workmen of several experienced concrete contractors may cause a maximum average variation in the compressive strength of the resulting concrete of 70 per cent or more.

(C) Relation of Consistency of Mixture to Compressive Strength.—The quantity of water added to the mixture in preparing concrete affects materially the compressive strength at all ages. With the proper quantity of water the strength may be several hundred per cent greater than that obtained with a large excess of water.

The most satisfactory consistency from the standpoint of strength and durability is a quaking or mushy mixture, and the error should be on the side of using too little rather than too much water, providing it is properly spaded or worked into place in the forms. This statement does not apply to the very dry mixtures used in the manufacture of concrete blocks, etc. In the case of these products the mixture should contain the maximum quantity of water which will permit of the immediate removal of the molds. This latter mixture has less water than the quaking consistency described above.

(D) Relation of Density to Compressive Strength.—With the same aggregates and the same proportion of cement to

total volume of aggregate the mixture having the greatest density will have a high and usually the highest compressive strength.

Density is no criterion of compressive strength of two mixtures of an aggregate if the ratio of cement to total volume of aggregate is not the same.

Density is no criterion of compressive strength of two mixtures of the same proportions of cement to total aggregate if different aggregates are used, although when the aggregates are quite similar they may be comparable.

(E) Effect of Various Exposures on Compressive Strength.—The character of the exposure of the concrete after molding materially affects its compressive strength. If the original water is permitted to evaporate from the concrete and all water is subsequently excluded, the compressive strength may be reduced 40 per cent or more. Concrete should preferably be kept wet for several days or weeks after it is deposited if the maximum strength is to be attained.

(F) Effect of Exposure to Steam on Compressive Strength.—Steam greatly accelerates the hardening process and will increase the strength of concrete only a few days old by several hundred per cent, depending on the temperature and duration of exposure.

(G) Relation of Gradation of Aggregate to Compressive Strength.—There is no definite relation between the gradation of the aggregate and the compressive strength which is applicable to any considerable number of different aggregates.

The gradation curve for maximum compressive strength, which is usually the same as for maximum density, differs for each aggregate.

The so-called maximum density curve, which is a combination of the straight line and ellipse, does not represent the curve for maximum density excepting for the particular materials used in the tests from which it was derived, or very similar materials.

No equation for a gradation curve, which can be applied to a number of different aggregates, can be prepared from the results included in this paper.

Maximum density and maximum strength are usually obtained with a concrete in which the ratio of fine to coarse aggregate is not less than 1 to 3. This mixture is usually quite stiff and therefore more difficult to handle than a mixture containing a larger percentage of fine aggregate.

Excessive fineness does not necessarily result in a totally unsatisfactory sand for concrete. A seashore sand having 99 per cent passing a 50-mesh sieve, when mixed with a good coarse aggregate and cement, was found to give a satisfactory concrete.

(H) Relation of Proportions to the Compressive Strength.—With the relative volume of fine and coarse aggregates fixed the compressive strength of a concrete increases directly as the cement content but not in a proportionate ratio. An increase in the ratio of cement to total fine and coarse aggregates when the relative proportions of the latter are not fixed does not necessarily result in an increase in strength. For example, a concrete mixed in the proportion of 1 part cement to 9 or 10 parts of total fine and coarse aggregates combined so as to give a maximum density may have greater strength than a concrete mixed in the proportion of 1 part cement to 6 parts total of the same fine and coarse aggregates, which are not combined to give a maximum density.

VII. CONCLUSIONS

1. No standard of compressive strength can be assumed or guaranteed for concrete of any particular proportions made with any aggregate unless all the factors entering into its fabrication are controlled.

2. A concrete having a desired compressive strength is not necessarily guaranteed by a specification requiring only the use of certain types of materials in stated proportions. Only a fractional part of the desired strength may be obtained unless other factors are controlled.

3. The compressive strength of a concrete is just as much dependent upon other factors, such as careful workmanship and the use of the proper quantity of water in mixing the concrete, as it is upon the use of the proper quantity of cement.

4. The compressive strength of concrete may be reduced by the use of an excess of water in mixing to a fractional part of that which it should attain with the same materials. Too much emphasis can not be placed upon the injurious effect of the use of excessive quantities of water in mixing concrete.

5. The compressive strength of concrete may be greatly reduced if, after fabrication, it is exposed to the sun and wind or in any relatively dry atmosphere in which it loses its moisture rapidly, even though suitable materials were used and proper methods of fabrication employed.

6. The relative compressive strength of concretes to be obtained from any given materials can be determined only by an actual test of those materials combined in a concrete.

7. Contrary to general practice and opinion the relative value of several fine aggregates to be used in concrete can not be determined by testing them in mortar mixtures. They must be tested in the combined state with the coarse aggregate.

8. Contrary to general practice and opinion the relative value of several coarse aggregates to be used in concrete can not be determined by testing them with a given sand in one arbitrarily selected proportion. They should be tested in such combination with the fine aggregate as will give maximum density, assuming the same ratio of cement to total combined aggregate in all cases.

9. No type of aggregate such as granite, gravel, or limestone can be said to be generally superior to all other types. There are good and poor aggregates of each type.

10. By proper attention to methods of fabrication and curing, aggregates which appear inferior and may be available at the site of the work may give as high compressive strength in concrete as the best selected materials brought from a distance, when the latter are carelessly or improperly used.

11. Density is a good measure of the relative compressive strength of several different mixtures of the same aggregates with the same proportion of cement to total aggregate. The mixture having the highest density need not necessarily have the maximum strength, but it will have a relatively high strength.

12. Two concretes having the same density but composed of different aggregates may have widely different compressive strength.

13. There is no definite relation between the gradation of the aggregates and the compressive strength of the concrete which is applicable to any considerable number of different aggregates.

14. The gradation curve for maximum compressive strength, which is usually the same as for the maximum density, differs for each aggregate.

15. With the relative volumes of fine and coarse aggregate fixed, the compressive strength of a concrete increases directly, but not in a proportionate ratio as the cement content. An increase in the ratio of cement to total fine and coarse aggregates when the relative proportions of the latter are not fixed does not necessarily result in an increase in strength, but may give even a lower strength.

16. The compressive strength of concrete composed of given materials, combined in definite proportions and fabricated and exposed under given conditions can be determined only by testing the concrete actually prepared and treated in the prescribed manner.

17. The results included in this paper would indicate that the compressive strength of most concretes, as commercially made, can be increased 25 to 100 per cent or more by employing rigid inspection which will insure proper methods of fabrication of the materials.

WASHINGTON, March 3, 1915.

TABLE 1

Physical Properties of Aggregates

Aggregate, Lab. No.	Results of tests given in tables—	Source of material: Location	Source of material: Character of sand deposit	Condition of grains	Specific gravity	Weight per cubic foot (pounds)	Percentage absorption	Percentage voids	Uniformity[a] coefficient	Granular analysis—percentage passing sieve No.— 6	10	20	30	40	50	80	100	200
Sand:																		
1	5 and 7	Columbus, Ohio	River	Rounded	2.50	92.3	1.30	39.5	2.45	84.6	29.0	3.6	1.5	1.0	0.8	0.6	0.6	0.5
2	5 and 7	Newark, Ohio	do	do	2.58	102.9	1.41	35.1	2.97	78.6	36.0	8.2	3.5	2.1	1.6	1.1	.9	.7
3	5 and 7	Pontiac, Mich		do	2.60	103.6	1.81	34.8	4.46	85.6	56.9	25.4	14.0	7.4	4.4	1.8	1.4	.8
4	5 and 7	Athens, Ohio		do	2.51	101.2	2.07	34.6	3.97	84.9	54.0	21.8	8.6	3.6	2.5	1.7	1.5	1.3
5	5 and 7	Peru, Ind		do	2.63	103.9	.88	36.3	3.11	87.4	60.3	22.9	8.0	2.0	.8	.2	.2	.1
6	5 and 7	Estherville, Iowa	River	do	2.59	102.5	.97	35.6	3.92	91.7	60.8	23.9	16.0	11.2	8.6	4.7	2.7	1.0
7	5 and 7	do	Pit	do	2.47	104.9	1.86	32.7	7.00	87.3	62.4	33.4	21.4	14.8	11.1	6.4	5.1	2.6
8	5 and 7	Pontiac, Ill	do	Medium sharp	2.45	100.0	2.87		6.48	88.2	55.9	32.4	24.4	14.0	7.4	2.6	2.0	1.4
9	5 and 7	Connersville, Ind	River	Rounded	2.59	107.4	1.94	33.1	4.63	85.8	62.1	33.8	21.6	10.0	4.8	1.5	1.0	.7
10	5 and 7	Waxahachie, Tex		do	2.35	92.9	4.51	35.6	7.10	90.4	64.9	33.9	21.2	14.7	11.7	7.7	6.7	3.9
11	5 and 7	Goshen, Ind		do	2.56	107.6	1.28	33.6	3.43	91.2	66.0	32.3	14.0	4.6	2.2	.9	.6	.3
12	5 and 7	Watertown, S. Dak	Pit	Sharp	2.59	103.2	.55	37.2	3.76	92.0	71.0	37.1	14.7	4.9	2.2	.9	.7	.6
13	5 and 7	Pittsfield, Mass	do	do	2.66	102.3	.27	38.7	4.06	89.8	70.2	37.4	21.6	13.2	10.3	7.2	6.4	3.6
14	5 and 7	Santa Cruz, Cal		do	2.53	97.4	.94	38.3	4.25	92.2	74.9	49.2	28.7	14.8	8.7	2.6	1.3	.5
15	5 and 7	Fort Collins, Colo	River	do	2.60	100.7	.13	38.2	5.47	92.5	75.6	46.7	30.0	18.5	12.6	5.2	3.1	.9
16	5 and 7	Greenville, Ill		Medium sharp	2.53	94.5	2.60	39.1	3.28	91.2	72.8	37.9	15.9	5.6	2.5	1.0	.7	.5
17	5 and 7	Estherville, Iowa	Pit	Rounded	2.45	101.6	2.15	32.3	6.84	93.5	66.5	35.7	22.4	15.6	12.2	6.6	4.9	3.2
18	5 and 7	Columbus, Ohio	River	do	2.49	99.3	1.70	36.0	5.03	90.5	63.8	36.4	21.2	11.4	7.1	3.4	2.4	1.2
19	5 and 7	Mahoning, Ohio			2.57	101.7	.59	36.5	3.87	86.0	69.2	44.7	30.3	7.9	5.4	2.0	.9	.2
20	5 and 7	Virginia, Minn	Pit	Sharp	2.59	97.3	.69	39.8	3.06	95.2	80.4	43.2	18.5	8.3	5.3	2.5	1.9	1.5
21	5 and 7	Dayton, Ohio	River	Rounded	2.59	103.5	1.08	34.7	4.03	91.2	70.8	40.5	22.7	11.0	6.1	1.5	.9	.6
22	5 and 7	Temple, Tex	do		2.51	102.5	1.43	35.1	3.32	90.1	69.2	48.8	35.0	20.0	10.4	2.4	1.3	.7
23	5 and 7	Fort Dodge, Iowa	Pit	Medium sharp	2.47	99.5	2.16	34.2	3.43	94.0	78.8	49.2	27.2	12.1	5.7	1.4	.9	.6
24	5 and 7	Huron, S. Dak	do	Sharp	2.49	101.7	2.25	33.1	5.50	89.8	70.0	48.2	35.7	21.2	12.9	3.2	1.7	1.2
25	5 and 7	Watertown, Wis		Rounded	2.58	108.8	.91	34.5	5.53	90.5	73.1	48.9	32.1	19.7	12.5	6.5	4.8	2.5

26	5 and 7	Wahoon, Ga	Creek	Sharp	2.57	90.8	.60	42.1	2.47	98.3	91.3	54.8	23.7	7.4	3.3	1.0	.7	.4
27	5 and 7	Ottawa, Iowa	River	Medium sharp	2.58	101.2	.94	37.1	2.88	95.9	82.3	50.4	26.6	7.1	2.4	.6	.4	.2
28	5 and 7	Columbus, Ind	do	Rounded	2.58	105.7	1.23	34.3	3.13	90.2	72.4	50.4	34.3	18.4	10.8	2.3	.8	.3
29	5 and 7	Columbus, Ohio	do	do	2.38	96.1	2.82	35.0	4.50	93.9	79.4	52.3	32.8	18.8	11.1	5.3	4.2	3.3
30	5 and 7	Concord, N. C		Sharp	2.41	92.9	1.28	36.2	5.12	98.2	86.8	51.7	30.8	19.1	14.0	8.0	6.0	3.0
31	5 and 7	High Point, N. C		do	2.44	92.6	.59	37.6	4.33	99.1	84.4	49.8	29.2	16.7	11.1	4.9	3.3	1.8
32	5 and 7	Beloit, Wis	River	do	2.41	106.1		26.8	3.58	99.9	72.6	54.8	35.3	18.4	4.3	.6	.4	.2
33	5 and 7	Goshen, Ind		Rounded	2.57	104.3	1.50	34.3	2.80	94.5	80.1	54.8	37.2	20.7	11.7	2.8	1.6	1.1
34	5 and 7	Roanoke, Va	River	do	2.35	91.0	2.29	37.0	3.60		86.0	52.4	38.3	22.1	13.2	3.4	1.7	.7
35	5 and 7	Louisville, Ky	do	do	2.56	102.1	.76	36.2	3.40	93.6	76.0	55.8	38.9	16.1	6.1	.3	.1	.0
36	5 and 7	Wabasha, Minn	Bank	Sharp	2.68	111.5		30.0	2.61	99.6	87.2	57.6	26.9	11.9	2.0	.4	.2	.1
37	5 and 7	Janesville, Wis	Pit	do	2.66	108.1		27.5	3.18	99.8	76.2	59.6	45.5	27.0	9.6	1.4	.5	.2
38	5 and 7	Litchfield, Ill			2.51	102.3	1.58	32.1	4.75	94.9	80.2	57.9	44.7	29.1	18.0	7.1	5.0	2.4
39	5 and 7	Brainerd, Minn		Rounded	2.56	105.4	.90	34.2	4.21	93.7	81.0	55.4	36.4	22.0	13.8	5.2	3.5	1.8
40	5 and 7	Clay Center, Kans	River	do	2.56	107.6	.34	33.0	4.88	94.4	79.7	56.3	38.5	23.7	17.7	5.2	2.1	.5
41	5 and 7	Athens, Ohio	Pit	do	2.52	94.7	1.19	37.9	2.57	97.9	90.9	64.5	31.7	11.1	3.2	.7	.6	.4
42	5 and 7	Oberville, N. Y		Medium sharp	2.52	98.7	1.10	36.7	3.94	97.2	87.7	64.1	44.7	26.6	17.6	8.5	6.0	2.9
43	5 and 7	Muskogee, Okla	River	Rounded	2.56	100.3	.38	37.0	2.37	96.3	87.3	64.3	37.1	14.1	6.2	1.1	.9	.5
44	5 and 7	Nombre de Diaz, C. Z	do		2.72	105.6		35.9	4.00	100.0	96.2	64.2	45.0	28.4	18.2	7.1	2.8	.2
45	5 and 7	Fort Mason, Cal							2.12	96.7	89.7	60.2	41.3	23.1	11.4	1.0	.4	.3
46	5 and 7	Sheridan, Wyo	Bank		2.54	95.7			4.16	97.0	87.9	61.5	38.5	21.5	13.4	6.0	4.2	2.2
47	5 and 7	do	River		2.56	97.3			3.61	96.9	86.3	61.9	40.8	23.2	14.4	5.9	3.9	2.0
48	5 and 7	Fredericksburg, Va		Sharp	2.50	86.6	1.40	43.8	2.84	98.7	90.5	63.2	35.0	16.5	9.3	3.0	1.9	1.0
49	5 and 7	Roanoke, Va			2.53	87.0			2.04		96.0	62.0	23.3	6.9	3.1	.9	.6	.4
50	5 and 7	Decorah, Iowa		Rounded	2.56	102.4	.66	35.5	2.78	96.1	86.7	63.4	40.4	19.3	8.7	1.8	1.1	.7
51	5 and 7	Lincoln, Ill		do	2.57	106.0	.68	34.2	6.18	94.3	78.5	62.3	50.3	34.5	19.0	5.0	2.5	.7
52	5 and 7	Unknown		do	2.42	87.4	2.00	41.8	2.95	98.0	90.9	62.5	40.4	22.3	10.6	2.1	.9	.2
53	5 and 7	do		do	2.55	105.2	1.19	34.3	3.77	92.4	81.1	63.5	43.8	25.2	15.9	6.5	4.5	2.8
54	5 and 7	do			2.68	102.5	.64	36.9	2.58	94.6	86.9	62.5	29.3	12.2	6.3	1.5	.8	.4
55	5 and 7	Fort Dodge, Iowa	Pit	Sharp	2.50	96.9	2.17	38.5	1.96	97.9	90.7	61.1	23.2	9.1	6.1	2.7	1.7	.9
56	5 and 7	do	do	Rounded	2.43	99.6	3.25	33.8	4.50	96.1	85.8	64.0	43.9	23.2	14.3	7.5	4.5	1.8
57	5 and 7	Bowling Green, Ky	River	do	2.35	87.2	2.96	39.9	3.15	94.1	80.2	63.6	45.9	20.1	11.9	1.8	1.5	.4
58	5 and 7	Lancaster, Ohio		do	2.54	101.3	1.67	36.0	3.70	96.3	86.8	64.5	44.7	26.5	17.0	6.5	4.1	2.3
59	5 and 7	Nombre de Diaz, C. Z	River		2.45	92.4		37.2	4.86	100.0	86.1	60.4	51.4	40.6	29.8	9.2	2.5	.2

[a] See p. 11.

TABLE 1—Continued

Physical Properties of Aggregates—Continued

Aggregate, Lab. No.	Results of tests given in tables—	Source of material: Location	Source of material: Character of sand deposit	Condition of grains	Specific gravity	Weight per cubic foot (pounds)	Percentage absorption	Percentage voids	Uniformity coefficient	Granular analysis—percentage passing sieve No.—: 6	10	20	30	40	50	80	100	200
Sand—Con.																		
60	5 and 7	Greenville, Ill			2.53	92.4	2.22	42.4	2.07	99.5	97.5	69.1	31.9	10.9	4.5	1.0	0.7	0.6
61	5 and 7	Olean, N. Y			2.47	94.2	.97	39.7	3.53	93.1	85.4	67.6	44.6	22.4	13.0	8.0	6.9	3.9
62	5 and 7	Fayetteville, N. C		Sharp	2.57	97.0	1.41	40.6	4.10	98.6	92.0	67.2	45.2	28.6	14.4	8.8	5.5	2.3
63	5 and 7	Muskogee, Okla	River	Rounded	2.56	102.6	.55	35.8	2.58	95.0	86.2	66.0	42.0	17.9	8.0	1.2	.7	.2
64	5 and 7	Louisville, Ky	Pit		2.55	101.7		30.3	2.81	99.8	84.5	67.7	47.7	26.8	11.2	2.8	1.7	1.0
65	5 and 7	Wichita, Kans	River	Sharp	2.62				3.53	100.0	83.6	65.4	50.9	33.3	20.6	4.9	1.3	.3
66	5 and 7	Lincoln, Ill		do	2.58	103.2	.66	36.3	3.47	97.4	86.2	68.3	44.0	27.4	15.0	3.7	2.1	.7
67	5 and 7	Bellingham, Wash	Puget Sound	do	2.62	100.2	.81	38.8	3.24	95.1	86.0	67.5	54.0	33.2	19.6	4.4	1.7	.2
68	5 and 7	Columbus, Ind	River	Rounded	2.56	104.2	1.08	35.5	3.12	88.0	76.8	65.7	56.6	41.3	21.2	3.9	2.2	1.0
69	5 and 7	Austin, Tex	Pit	Medium sharp	2.57	102.4	1.25	33.7	3.50	93.9	82.8	66.6	44.9	23.4	12.7	3.5	2.3	1.4
70	5 and 7	Wilmer, Minn			2.09	89.3	6.41	29.6	3.62	97.4	89.9	68.8	47.4	27.3	19.6	6.3	2.9	1.0
71	5 and 7	Osage Junction, Okla	River	Rounded	2.59	101.9	.37	36.2	3.26	98.5	90.6	67.3	46.9	26.6	13.8	2.6	.6	.2
72	5 and 7	Fort Dodge, Iowa	Pit	do	2.50	96.6	1.53	36.6	2.90	97.7	91.1	69.8	45.0	25.7	12.2	2.3	1.5	1.0
73	5 and 7	Unknown		do	2.60	104.4	.79	36.0	3.64	93.3	82.8	70.1	54.4	32.3	17.8	3.6	1.3	.4
74	5 and 7	Plattsmouth, Nebr	River	do	2.58	109.3	.78	32.4	2.75	97.1	90.0	72.0	59.4	41.5	27.0	5.5	1.7	.1
75	5 and 7	Lincoln, Ill		Sharp	2.57	101.1	.66	36.8	2.93	98.1	92.5	73.7	58.0	38.4	23.2	4.6	1.7	.2
76	5 and 7	Pittsfield, Mass	Pit	do	2.71	93.1	.82	43.4	3.70		98.2	74.1	43.1	23.7	17.0	8.7	6.8	2.2
77	5 and 7	Unknown			2.50	91.0		36.4	2.93	100.0	85.2	72.0	61.9	46.1	31.1	7.5	2.0	.2
78	5 and 7	Louisville, Ky	River	Sharp	2.61	100.0		36.6	2.28	100.0	82.0	73.3	64.9	45.8	19.9	1.7	.6	.2
79	5 and 7	do	Pit	do	2.62	100.8		32.5	2.14	99.8	85.9	71.6	58.2	33.8	9.4	1.5	.9	.6
80	5 and 7	do			2.88	101.4		33.1	2.42	99.9	84.4	71.3	59.2	36.8	14.8	3.0	1.8	1.0
81	5 and 7	Pontiac, Mich	Pit	Medium sharp	2.60	100.0	.68	38.0	2.62	98.4	92.5	74.4	49.4	22.2	11.3	2.9	1.7	.9
82	5 and 7	Unknown		do	2.63	107.0	.54	33.8	2.84	93.1	84.7	70.4	48.3	24.2	12.7	2.3	1.0	.4
83	5 and 7	Salisbury, N. C			2.50	88.1			3.50	97.5	93.6	69.9	46.8	28.7	18.8	6.6	3.8	1.7

84	5 and 7	Great Falls, Mont	Tailings	Sharp	2.65	93.7	.46	43.2	2.62	99.6	99.0	71.8	44.2	19.9	10.3	2.4	1.2	.4
85	5 and 7	Cowe Bay, Long Island		do	2.62	97.1	.21	40.6	3.14	97.1	91.4	74.8	59.4	41.9	26.1	9.5	6.3	2.4
86	5 and 7	Eagle Pass, Tex	River	Rounded	2.48	101.2	1.71	35.3	3.00	98.4	89.4	79.1	71.7	63.9	57.5	29.5	19.2	7.4
87	5 and 7	Wichita Falls, Tex		do	2.56	97.5	.38	39.1	3.00	97.7	90.2	75.5	54.0	23.8	15.3	7.1	4.7	1.3
88	5 and 7	Maryville, Mo	Pit	do	2.55	94.1	.83	40.8	2.55	98.1	92.9	77.4	58.7	31.8	16.1	4.0	2.4	1.2
89	5 and 7	Mount Clemens, Mich	River	Medium sharp	2.58	97.5	1.09	39.4	2.63	99.0	95.1	77.3	53.5	27.1	13.9	2.6	1.2	.7
90	5 and 7	Hillsdale, Mich		Rounded	2.58	103.4	1.49	34.1	2.87	96.9	89.5	76.4	62.5	41.4	26.9	9.5	5.3	1.4
91	5 and 7	Lacrescent, Minn	Bank	Sharp	2.63				2.20	99.8	93.2	77.5	44.1	16.2	5.2	1.1	.5	.3
92	5 and 7	Beloit, Wis	Glacial	do	2.66	103.5		30.7	2.26	99.9	90.4	76.2	62.0	40.0	14.0	1.9	.7	.2
93	5 and 7	Topeka, Kans	River	do	2.62				2.94	100.0	93.3	76.7	58.0	35.7	21.1	6.4	2.8	.4
94	5 and 7	Belvidere, Ill		Rounded	2.51	103.0	1.02	33.9	2.75	98.5	90.7	77.3	59.3	36.1	22.3	4.9	2.2	.8
95	5 and 7	Maryville, Mo	Pit	Sharp	2.54	94.2	1.00	40.1	2.44	99.4	95.3	81.1	60.7	32.1	15.7	3.0	1.8	1.1
96	5 and 7	Green Castle, Ind		Rounded	2.58	98.4	.55	39.5	2.29	95.7	90.5	81.0	68.6	43.4	20.8	3.1	1.5	.8
97	5 and 7	Brattleborough, Vt		Sharp	2.67	96.0	1.99	42.0	2.96	99.9	99.2	82.7	51.8	27.7	16.8	5.6	3.0	1.0
98	5 and 7	Malone, N. Y		Rounded	2.62	97.1	.63	40.8	2.80	99.5	98.3	83.9	64.2	38.6	23.1	7.3	4.4	1.8
99	5 and 7	Santa Barbara, Cal	Creek	Sharp	2.44	91.8	1.47	39.8	4.22	96.7	90.9	80.6	67.6	48.3	34.1	16.8	8.2	3.3
100	5 and 7	Windhern County, Vt	Bank	do	2.72	95.1	.46	44.6	2.55	99.4	98.8	82.0	50.9	23.9	12.5	3.8	2.3	.6
101	5 and 7	Aiken, S. C		do	2.63	92.3	.49	43.3	3.52	96.0	93.9	81.9	68.7	48.0	33.9	13.8	6.9	.8
102	5 and 7	Faribault, Minn	Pit	do	2.55	100.1	.81	37.3	2.33	97.6	92.2	82.5	73.3	54.6	36.7	8.1	3.4	.7
103	5 and 7	Estherville, Iowa	River		2.52	98.5	1.10	37.6	2.80	97.2	91.8	84.2	75.8	63.1	52.2	23.0	13.1	3.0
104	5 and 7	Ottumwa, Iowa	Pit	Sharp	2.63	103.7		33.3	1.86	100.0	94.9	83.8	66.8	37.0	11.5	1.0	.3	.1
105	5 and 7	Peru, Ind		Rounded	2.55	97.1	1.10	38.9	8.67	97.8	93.0	83.6	72.6	57.1	40.5	7.8	3.0	.7
106	5 and 7	Lexington, Mo	River	do	2.59	104.7	.30	35.4	2.14	98.2	94.4	80.6	62.1	36.3	25.3	9.9	5.3	2.1
107	5 and 7	Kinston, N. C		Medium sharp	2.62	92.2	.23	42.8	2.84	99.3	98.1	85.7	66.2	43.5	28.5	7.1	2.6	.4
108	5 and 7	Unknown		Sharp	2.40	87.3	.90	40.2	2.39	97.4	94.4	87.8	76.7	52.9	35.5	8.1	2.8	.5
109	5 and 7	Newark, Ohio	River	Rounded	2.59	91.2	.38	43.6	1.82	99.1	94.6	86.1	66.9	22.3	8.3	1.2	.5	.3
110	5 and 7	Charleston, W. Va	do	Sharp	2.54	88.8	.42	44.7	2.12	99.1	96.3	88.6	77.1	47.7	23.6	3.9	2.0	1.1
111	5 and 7	Westfield, Mass		do	2.64	94.0	.77	43.0	2.58	99.4	97.4	87.8	70.8	48.0	31.5	9.1	4.0	.9
112	5 and 7	Nombre de Diaz, C. Z	River	do	2.67	89.0		46.2	2.65	100.0	99.9	86.4	59.0	35.0	19.6	5.5	2.6	.6
113	5 and 7	Easton, Pa	do	Medium sharp	2.52	88.5	1.08	43.6	1.92	99.2	97.2	86.6	55.4	16.4	4.4	.5	.2	.1
114	5 and 7	Brainerd, Minn		Rounded	2.58	94.8	.74	41.2	2.36	98.9	96.4	85.8	68.5	42.5	22.6	3.7	1.6	.8
115	5 and 7	Wilmer, Minn	Lake	Sharp	2.58	98.9	.48	39.4	5.56	98.3	95.0	86.0	73.3	49.6	29.1	8.9	5.0	1.0
116	5 and 7	Mount Alta, Pa		Medium sharp	2.57	83.2	1.82	46.3	3.30		98.9	89.5	70.9	46.7	33.0	13.2	7.6	3.9
117	5 and 7	Quincy, Ill	River	Rounded	2.59	98.2	.30	39.4	2.12	99.5	98.7	90.4	73.8	44.0	22.3	2.3	.4	.1
118	5 and 7	Leavenworth, Kans	do	Sharp	2.63				1.78	99.8	97.6	90.4	70.8	23.7	7.5	1.1	.7	.3

TABLE 1—Continued

Physical Properties of Aggregates—Continued

Aggregate, Lab. No.	Results of tests given in tables—	Source of material: Location	Source of material: Character of sand deposit	Condition of grains	Specific gravity	Weight per cubic foot (pounds)	Percentage absorption	Percentage voids	Uniformity coefficient	Granular analysis—percentage passing sieve No.— 6	10	20	30	40	50	80	100	200
Sand—Con.																		
119	5 and 7	Fredericksburg, Va	River	Sharp	2.54	83.2	0.51	47.9	1.72	99.3	98.2	91.0	61.9	16.6	6.2	1.9	1.1	0.5
120	5 and 7	La Salle, Ill		Medium sharp	2.53	93.0	1.13	41.4	5.19	98.5	96.5	90.9	79.2	54.8	27.9	5.0	2.4	1.0
121	5 and 7	Dixon, Ill	Pit	Sharp	2.62	96.2	.17	40.9	1.30	99.2	97.2	92.4	76.4	27.6	8.1	.9	.3	.2
122	5 and 7	Greenville, Ill		Medium sharp	2.56	93.5	.87	41.6	2.10	99.7	99.4	91.9	65.6	29.2	12.2	1.6	.6	.2
123	5 and 7	Sheridan, Wyo	River		2.50	88.2	.89	43.6	2.33	99.6	99.2	93.2	77.4	52.8	31.9	8.5	4.8	2.1
124	5 and 7	Brainerd, Minn		Rounded	2.59	96.1	.32	41.5	2.67	99.3	98.7	93.8	86.8	74.4	55.5	20.5	11.3	1.4
125	5 and 7	Burlington, Iowa	River	Sharp	2.64				1.76	100.0	98.9	93.5	78.8	50.8	18.1	3.8	1.0	.1
126	5 and 7	Rockton, Ill	Pit	do	2.65	98.3		34.8	1.88	99.8	97.8	94.3	83.2	59.1	24.9	3.2	1.0	.1
127	5 and 7	Wichita Falls, Tex		Medium sharp	2.58	95.3	.43	41.4	1.90	99.4	97.8	95.1	82.1	30.7	11.3	3.3	2.4	.6
128	5 and 7	Billings, Mont	Bank		2.58	91.3	.84	43.4	3.00	99.2	98.0	95.9	87.5	60.9	39.9	15.8	8.9	3.2
129	5 and 7	Pendleton, Oreg	River	Sharp	2.70	101.5	.64	39.1	2.42	100.0	99.8	96.5	63.0	26.2	13.4	3.5	1.8	.5
130	5 and 7	Junction City, Ga		do	2.62	91.4	.24	43.9	3.30	99.6	99.6	95.3	81.6	62.4	47.8	20.1	11.0	2.7
131	5 and 7	Charleston, W. Va	River	do	2.57	86.4	.44	45.8	1.95	99.4	99.0	95.9	81.0	40.2	15.3	2.9	1.8	.9
132	5 and 7	Sturgisson, W. Va		do	2.58	90.0	.29	44.0	3.33	100.0	99.7	97.1	86.8	61.1	33.8	8.4	4.4	1.0
133	5 and 7	Great Falls, Mont	Tailings	do	2.72	94.2	.53	42.8	1.91	100.0	99.5	69.2	39.9	21.0	11.7	3.1	1.5	.7
134	5 and 7	Lincoln, Ill		do	2.56	94.4	.84	41.3	2.36	99.4	98.5	94.4	88.2	73.4	43.7	13.9	7.7	1.4
135	5 and 7	Unknown		Medium sharp	2.62	94.3	.46	41.5	1.43	99.9	99.8	99.4	89.4	37.5	13.7	1.7	.7	.3
136	5 and 7	Dayton, Ohio	Bank	do	2.57	97.5	1.04	39.6	3.83	98.7	97.7	94.0	89.7	75.3	59.3	30.9	19.4	7.6
137	5 and 7	Carrollton, Mo	do	Sharp	2.54	91.6	.80	41.9	2.81	99.7	99.3	96.6	89.6	78.8	56.7	14.6	5.0	.6
138	5 and 7	Armitage, Ohio	do	Rounded	2.58	88.8	.51	45.2	2.12	99.3	99.1	97.6	91.3	48.9	27.6	3.9	2.1	.5
139	5 and 7	Dayton, Ohio	Pit	Sharp	2.58	90.3	1.09	44.6	2.50	100.0	99.3	97.7	92.2	81.0	72.7	25.1	11.5	1.6
140	5 and 7	do	Bank	do	2.55	93.4	.93	41.5	3.11	100.0	99.4	98.5	92.4	64.0	43.1	19.6	10.0	2.0
141	5 and 7	Devils Lake, N. Dak		Rounded	2.51	88.8	.88	43.6	1.92	99.5	99.1	97.6	92.1	76.1	52.9	11.1	4.8	1.9
142	5 and 7	Big Stone Gap, Va	River	Sharp	2.47	86.6	.97	44.7	3.25	99.2	98.5	98.0	92.5	71.8	48.1	20.1	12.2	4.4

143	5 and 7	Greenville, Ill			2.48	82.8	.37	46.3	1.66	99.3	98.5	96.9	92.8	82.1	68.3	23.3	17.8	7.8
144	5 and 7	Albany, Ga		Sharp	2.63	87.5	.22	46.1	1.87	100.0	99.5	93.6	71.4	47.4	9.1	2.8	.3	
145	5 and 7	Chambersburg, Pa		do	2.49	73.0	.45	55.0	3.00	99.6	99.5	99.2	94.1	69.6	41.7	13.1	8.4	3.5
146	5 and 7	Somerset, Ky		do	2.46	88.5	1.35	42.1	3.33	100.0	99.2	98.4	96.0	87.7	70.3	32.2	15.7	7.2
147	5 and 7	Billings, Mont	Bank		2.62	88.7	.57	45.8	2.10	99.5	99.3	99.1	96.1	82.3	63.9	23.4	10.3	1.8
148	5 and 7	Mansfield, Ohio	Glacial	Rounded	2.54	87.3	.73	45.4	1.92	100.0	100.0	98.9	97.5	81.1	43.6	11.3	6.2	2.2
149	5 and 7	Lynchburg, Va		Sharp	2.34	79.9	1.88	43.1	2.29		99.7	99.5	96.5	75.0	51.6	13.4	6.3	2 0
150	5 and 7	Great Falls, Mont	River		2.48	84.1	.93	45.6	1.86	99.6	99.3	99.2	98.2	69.9	28.6	6.6	2.1	.3
151	5 and 7	Bowling Green, Ky	do	Rounded	2.34	78.9	1.51	45.4	4.50	99.6	98.0	95.9	93.9	90.2	76.8	41.1	27.3	12.0
152	5 and 7	Michigan City, Ind	Dune	do	2.60	93.0	.16	43.0	1.34	100.0	99.8	99.7	98.8	91.3	65.9	7.2	1.0	.0
153	5 and 7	Brainerd, Minn	River	do	2.58	93.6	.53	41.3	2.56	99.2	99.0	98.0	96.7	94.3	88.7	38.4	19.3	5.2
154	5 and 7	Klondike, Mo		Medium sharp	2.61	93.6	.22	42.4	2.11	100.0	99.7	99.5	98.7	94.5	82.1	24.8	10.3	1.3
155	5 and 7	Michigan City, Ind	Lake	Rounded	2.59	92.3	.20	43.1	1.34	100.0	99.8	99.8	99.4	94.9	78.8	8.8	.9	.1
156	5 and 7	Great Falls, Mont	River	Sharp	2.57	85.7	1.64	45.0	2.71	99.5	99.4	99.3	99.2	97.6	80.7	34.4	19.8	3.0
157	5 and 7	Manitowoc, Wis		Rounded	2.70	94.8	.32	43.3	1.52	100.0	100.0	100.0	100.0	97.1	84.1	13.1	3.1	.5
158	4	Kansas City, Mo	River		2.64	109.3	.20	33.6	5.46		96.8	86.5	57.2	27.4	20.7	19.5	16.1	1.3
159	4	do	do		2.65	107.7	.39	34.8	2.32		94.6	69.2	43.2	17.5	4.7	.5	.1	
160	4	Columbus, Ohio	do		2.60	103.3		36.3	5.43		75.3	52.1	37.1	23.9	14.5	7.9	6.0	4.1
161	4	Symmes, Ohio	Bank		2.63	114.4		29.0	3.97		67.0	32.1	16.9	8.5	4.1	2.0	1.6	1.3
162	4	Cincinnati, Ohio	River		2.59	104.8	1.06	35.1	2.73		81.5	58.8	39.1	15.7	4.3	1.0	.7	
163	4	St. Charles, Ohio	Bank		2.67	113.5	2.11	31.8	2.98		84.5	68.6	52.6	32.1	14.4	5.3	3.6	1.7
164	4	Carpenterville, Ill	do		2.68	116.0	.96	30.6	2.33		92.6	78.2	61.2	37.9	16.5	4.5	2.6	1.5
165	4	Algonquin, Ill	do		2.68	114.5	1.31	31.5	4.96		69.3	47.1	32.9	19.2	8.5	2.5	1.6	1.0
166	4	Libertyville, Ill	do		2.60	110.5	1.39	31.8	4.91		68.9	51.6	39.4	24.4	10.0	3.5	2.5	1.7
167	4	Kenton County, Ky	do		2.62	110.0	1.41	32.7	2.78		93.6	81.6	67.3	48.7	27.2	9.2	4.6	1.6
168	4	Toledo, Ohio	(a)		2.71	108.3	3.63	35.9	6.38		67.6	46.7	37.0	28.9	20.1	9.2	5.9	3.6
169	4	do	(a)		2.70	106.5		36.7	7.58		66.7	42.0	30.2	22.7	15.5	8.2	5.8	3.6
170	4	Chilson, Mich	Bank		2.70	119.5	1.63	29.0	4.88		69.1	38.7	24.3	14.3	7.6	2.4	1.4	1.0
171	4	St. Claire River, Mich	River		2.64	111.0	2.61	33.2	4.27		92.6	70.2	58.2	44.9	29.7	14.6	7.8	2.1
172	4	do	do		2.63	95.5		41.8	1.69		99.0	97.2	95.2	86.7	61.4	16.7	7.1	2.6
173	4	do	do		2.69	119.5	1.59	28.7	5.10		60.5	33.0	21.4	12.0	5.2	2.2	1.4	1.0
174	4	Utica, Mich	Bank		2.62	105.5	1.53	35.4	2.55		91.6	84.1	76.3	62.0	37.8	12.4	6.3	2.7
175	4	Attica, Ind	do		2.64	106.5		35.3	4.20		95.9	79.6	63.6	44.6	30.8	14.5	10.4	5.4
176	4	do	do		2.65	119.9	1.19	27.4	4.45		72.9	46.0	29.6	15.3	8.1	2.9	2.1	1.5

a Limestone screenings and sand.

TABLE 1—Continued

Physical Properties of Aggregates—Continued

Aggregate, Lab. No.	Results of tests given in tables—	Source of material: Location	Source of material: Character of sand deposit	Condition of grains	Specific gravity	Weight per cubic foot (pounds)	Percentage absorption	Percentage voids	Uniformity coefficient	Granular analysis—percentage passing sieve No.— 6	10	20	30	40	50	80	100	200
Sand—Con.																		
177	4	Attica, Ind	Bank		2.63	116.5		29.0	5.62		77.7	50.2	36.3	24.6	16.9	5.2	3.2	2.0
178	4	Moselle, Mo	River		2.61	89.0		45.3	1.70		99.0	91.7	84.1	64.1	20.6	2.6	1.0	.8
179	4	Drake, Mo	do		2.60	98.8		39.1	2.70		92.7	69.0	54.7	33.1	17.3	2.2	.5	.1
180	12, 14, 15, 16	do	do		2.61	97.7		37.8			99.0	91.7	84.1	64.1	20.6	2.6	1.0	.8
181	2, 8, 9, 12, 14, 15, 16, 17, 22, 25, 30, 34	do	do		2.60	100.6		37.7			97.0	81.5	64.0	37.0	13.9	3.6	1.3	.2
182	8, 9, 14, 15, 16, 37	do	do			105.3		34.9										
183	3, 6, 8 to 15, 16, 18, 20, 29, 31, 33, 34, 35, 35, 37	do	do		2.58	99.5		38.0		99.89	92.6	68.9	54.7	33.0	17.2	2.1	.4	.1
184	4, 8, 9, 13, 14, 23, 35	Nombre de Diaz, C. Z.			2.73	105.6	1.25	37.9			96.2	64.2	45.0	28.4	18.8	7.1	2.8	.2
185	4, 8, 9, 13, 14, 23, 35	Quango Beach, C. Z.	Beach		2.51	91.0	2.64	41.7			85.2	72.0	61.9	46.0	31.1	7.5	2.0	.2
186	2, 8, 9, 10, 11, 13, 14	Point Chame, C. Z.			2.54	92.8		41.4		99.8	99.6	87.4	69.2	50.2	35.2	9.9	2.6	.4
187	19	New Jersey	River			86.5					93.1	82.7	73.4	56.1	41.9	12.1	7.9	.9
188	19	Atlantic City, N. J.	Beach			89.5					99.7	99.6	99.5	99.4	98.8	64.1	45.0	2.5

189	28,21	Washington, D. C	River							93.2	81.8	73.3	63.9		23.6		5.2	
190	24	Long Island			2.61	96.7		40.5		96.5	89.3	73.0	56.1	37.3	24.5	9.0	4.9	2.1
191	4	Canal Zone			2.45	92.4	5.31	37.2			86.1	60.4	51.4	40.7	29.9	9.2	2.5	.2
192	3	New Jersey									87.0	68.6	54.1	38.5	29.1	10.5	6.6	
193	3	Long Island									88.4	76.1	62.5	46.2	37.6	19.0	14.4	
194	26	Chame, C. Z.	River		2.64	95.0		44.4			99.6	96.2	78.8	59.3	46.1		9.3	
195	26,27	Chagres River, C. Z.	do		2.72	102.0		40.0			71.4	52.1	35.3	22.8	16.3		4.4	
196	37	Drake, Mo	do															
197	34																	
198	25,34																	
199	25,34																	
200	31a	Elsinboro	River	Sharp	2.64	88.0		46.6		98.6	86.8	71.3	a56.9	b39.3	c15.3	d4.5	1.5	
201	31a	Ocean City, Del	Beach	Rounded	2.69	90.0		46.2		100.0	99.9	99.6	a96.0	b84.3	c41.6	d12.8	2.5	
202		Lancaster, Pa			2.68	98.4		41.3		92.3	76.2	59.8	a47 3	b38.5	c30.9	d26.4	22.4	
Gravel screenings:																		
301	4	Meramec River, Mo	do		2.56	115.0	1.09	28.0	8.78		38.0	25.6	19.3	11.6	4.1	.5	.2	.2
302	4	Moselle, Mo	do		2.57	113.5	1.61	29.2	9.00		62.2	47.7	39.9	30.3	17.2	3.9	1.7	.9
303	4	Columbus, Ohio	do		2.66	102.6	1.70	38.2	19.78		21.0	16.0	13.4	11.8	10.1	9.2	8.4	6.7
304	4	Loveland, Ohio	Bank		2.67	117.1	.72	29.7	3.35		72.0	60.7	49.2	29.4	13.5	4.6	2.9	1.1
305	4	Carthage, Mo	do		2.67	115.3	1.80	30.7	4.96		61.0	37.0	23.0	12.0	3.5			
306	4	Ludlow, Ky	do		2.72	120.8	1.02	28.8	13.07		53.8	37.7	30.8	23.0	14.9	7.9	5.3	3.1
307	4	Chilson, Mich	do		2.68	113.4	0.71	32.1	1.80		4.5	.0						
308	4	do	do		2.70	111.5	1.31	33.8	1.99		2.3	1.0	.0					
309	4	Amhersburg, Canada	River Beach		2.66	117.8	1.65	29.0	2.08		.7	.0						
310	4	Loraine, Ohio	Lake		2.68	118.9	.50	28.9	5.50		66.8	50.8	41.5	31.4	17.1	2.4	1.0	.2
311	4	Attica, Ind	Bank		2.68	122.5	1.10	26.7	5.74		54.7	23.6	14.9	7.8	3.8	1.5	1.0	.8
312	4	do	do		2.67	120.3	1.36	27.8	5.26		73.9	50.8	37.7	23.7	14.1	3.6	1.7	.7
Stone screenings:																		
401	4	St. Louis, Mo	Limestone		2.70	103.5	.67	38.5			63.2	40.7	28.4	20.6	15.2	9.8	7.1	2.2
402	4	do	do		2.70	106.2	.55	36.9			59.5	38.4	28.4	20.7	15.6	10.7	8.6	3.0
403	4	do	do		2.67	103.5	1.31	37.8			65.4	52.6	43.3	34.6	27.0	20.1	15.1	2.0
404	4	Glencoe, Mo	do		2.65	105.5	.91	37.4			26.1	20.1	14.9	11.9	9.7	7.5	6.0	1.5

a No. 28 sieve. Tyler Screen Scale. b No. 35 sieve. Tyler Screen Scale. c No. 48 sieve. Tyler Screen Scale. d No. 65 sieve. Tyler Screen Scale.

TABLE 1—Continued

Physical Properties of Aggregates—Continued

Aggregate, Lab. No.	Results of tests given in tables—	Source of material		Condition of grains	Specific gravity	Weight per cubic foot (pounds)	Percentage absorption	Percentage voids	Uniformity coefficient	Granular analysis—percentage passing sieve No.—								
		Location	Character of sand deposit							6	10	20	30	40	50	80	100	200
Stone screenings—Con.																		
405	4	Springfield, Mo	Limestone		2.66	95.7	0.55	42.3			21.6	11.5	8.2	6.1	4.9	3.0	2.1	1.2
406	4	Joplin, Mo	Chat		2.61	109.5	.76	32.7			31.8	21.2	17.8	15.8	14.3	12.6	11.8	9.4
407	4	do	do		2.63	102.7	2.36	37.1			52.9	28.3	18.1	12.9	9.3	6.6	5.7	3.8
408	4	do	do		2.61	105.5	1.90	35.2			48.7	27.6	19.2	14.3	10.6	6.8	5.3	3.1
409	4	do	do		2.62	108.0	2.73	33.9			46.4	27.9	20.1	15.3	11.4	7.4	5.9	3.4
410	4	do	do		2.62	109.8	1.05	32.8			50.2	30.0	22.4	16.5	12.4	9.8	7.7	4.9
411	4	St. Louis, Mo	Limestone		2.70	95.5	2.74	43.3			90.1	59.8	46.1	49.2	32.0	24.1	20.5	2.0
412	4	Kansas City, Mo	do		2.64	105.3	1.54	36.0			68.8	45.2	34.2	26.8	21.6	15.1	13.2	1.9
413	4	St. Joseph, Mo	do		2.71	102.2	1.79	39.5			61.6	27.8	14.1	9.2	7.4	6.0	4.9	.4
414	4	Kansas City, Mo	do		2.63	104.3	1.42	36.6			45.1	26.1	18.7	14.4	11.6	8.8	7.3	3.5
415	4	Hoffman, Mo	Chat		2.84	109.5	1.28	35.9			43.1	7.8	2.5	1.3	1.0	.9	.9	.8
416	4	Bonnetere, Mo	do		2.86	120.0	1.13	32.7			72.6	38.4	23.0	15.5	10.0	5.6	4.2	2.7
417	4	Graniteville, Mo	Granite		2.70	108.8	.32				50.3	27.5	18.8	14.4	10.3	7.1	5.9	3.2
418	4	Kankakee, Ill	Limestone		2.70	103.8	2.11	38.3			51.3	33.5	25.8	20.3	16.8	13.2	11.8	8.7
419	4	McCook, Ill	do		2.78	102.5	1.06	40.9			77.1	39.5	26.0	17.1	13.0	9.9	8.6	5.5
420	4	Columbus, Ohio	Bowlder		2.69	108.5	2.52				38.5	31.4	29.0	27.2	26.0	24.3	23.1	18.9
421	4	Hillsboro, Ohio	Limestone		2.71	97.4	.04	42.4			94.2	80.1	71.6	62.8	52.7	39.1	29.7	15.6
422	4	Greenfield, Ohio	do		2.72	106.3	2.05	37.3			55.6	34.2	25.7	20.8	17.4	14.4	12.9	8.9
423	4	Casparis, Ohio	do		2.65	99.7	.13	39.7			43.0	29.2	22.6	18.3	14.4	10.4	9.3	5.4
424	4	Sylvania, Ohio	do		2.72	101.1	1.86	40.4			13.0	6.2	4.7	4.1	3.6	3.1	3.1	2.6
425	4	Sibley, Mich	do		2.70	110.3		34.5			53.7	36.7	30.1	25.3	22.2	18.7	17.1	4.9
426		Minnesota City, Minn	do		2.56	101.2	3.13	36.6			91.8	79.7	22.9	68.5	64.2	54.8	46.6	25.6
427	34	Shoshone, Wyo	Granite		2.49	101.4	1.90	34.60		85.10	66.3	47.0	36.6	28.7	23.8	15.8	12.2	6.8

428	3	Jersey City, N. J	Trap									49.9	29.7	23.8	18.3	15.7	10.7	9.2	
429	26, 27	Ancon, C. Z.	do		2.56	80.7		49.5			70.8	54.3	44.5	32.9	29.2		18.3	
430		Mascot, Tenn	Chat		2.86	112.0		37.1		[ab]37.9	23.6	15.4	[c]10.5	[d]7.2	[e]4.2	[f]2.5	1.3	
431		do	Chat [g]		2.90	95.5		47.2				99.7	[c]97.8	[d]91.7	[e]71.9	[f]52.4	28.2	
432		Webb City, Mo	Chat	Mine run	2.60	98.0		39.6		[ah]25.6	8.6	3.3	[c]1.84	[d]1.24	[e].90	[f].54	.44	
433		do	do	Retained on ⅛-inch screen.	2.62	89.5		45.8		[i]25.9	0.8							
434		do	do	Passing ⅛-inch screen.	2.64	95.0		42.4		99.3	89.0	57.0	[c]40.6	[d]29.6	[e]18.9	[f]12.4	6.4	
Slag sand:																		
501	4				2.44	82.9		45.5			84.3	45.4	34.0	11.4	5.8	2.1	1.4	.6

[a] All material passed ½-inch sieve.
[b] No. 3=74.0, No. 4=52.4.
[c] No. 28 sieve. Tyler Screen Scale.
[d] No. 35 sieve. Tyler Screen Scale.
[e] No. 48 sieve. Tyler Screen Scale.
[f] No. 65 sieve. Tyler Screen Scale.
[g] Fine tailings from Wilfley Tables.
[h] No. 3=61.4, No. 4=41.7.
[i] No. 3=73.2, No. 4=49.9.

TABLE 1a

Physical Properties of Aggregates

PIT AND CRUSHER RUN MATERIAL

Aggregate, Lab. No.	Results of tests in tables—	Location	Specific gravity	Weight per cubic foot (pounds)	Per cent voids computed	Per cent absorption	Granular analyses—per cent passing screen— 2-inch	1¾-inch	1½-inch	1¼-inch	1-inch	¾-inch	½-inch	¼-inch
Granite:														
175	8, 9, 14, 15, 16, 17, 22, 35	St. Louis, Mo	2.598	99.1	37.6	0.19	......	......	......	99.98	99.71	99.29	57.54	19.88
212	8, 9, 10, 11, 12, 13, 14, 15, 16	Marble Falls, Tex	2.635	91.6	44.3	1.50	......	......	99.70	98.12	86.60	77.95	56.20	......
317	8, 9, 10, 12, 13, 14, 15, 36	St. Louis, Mo	2.603	86.3	46.3	.33	......	......	......	100.00	99.44	97.50	51.02	12.58
449	34	Shoshone, Wyo	2.651	95.1	42.3	.19	99.99	93.57	86.72	79.24	61.84	52.30	30.07	10.71
Trap rock:														
505	19	New Jersey	......	91.0	......	......	......	......	......	100.00	97.19	78.91	26.06	3.38
506	8	Bergen Hill, N. J	......	......	......	......	......	......	......	......	......	......	......	......
524	27	Ancon, C. Z	2.500	82.1	47.2	......	[a] 64.0	......	27.0	......	2.8	1.0	0	......
525	26, 27	do	2.500	82.1	47.2	......	100.0	......	99.0	......	75.0	59.2	40.5	15.5
450	8, 9, 10, 11, 13, 14	Ancon Hill, C. Z	2.507	77.2	50.6	......	[b] 84.67	51.79	29.21	16.40	5.75	4.08	2.45	1.53
508	......	Delaware	2.680	90.0	48.5	......	......	......	98.1	......	55.1	41.4	18.6	0.5
Limestone:														
30	12, 14, 15	Cleveland, Ohio	2.710	92.2	44.6	4.34	......	......	......	100.00	95.00	83.00	62.00	37.25
31	12, 14, 15	Casparis, Ohio	2.660	96.5	40.9	.59	100.00	98.37	91.31	80.37	55.12	36.36	12.12	4.25
81	12, 14, 15	......	2.700	106.5	35.7	1.03	......	......	100.00	99.50	87.90	66.70	31.00	14.80
128	8, 9, 12	Milwaukee, Wis	2.637	92.6	56.4	1.26	......	......	99.37	98.01	85.30	67.84	32.68	16.62
133	8, 9, 12, 14, 15	Greenleaf, Wis	2.634	103.8	37.9	1.32	......	......	99.92	96.80	79.91	59.20	28.05	12.60
136	8, 9, 12, 13, 14, 15	Madison, Wis	2.606	94.6	41.8	1.46	......	......	99.70	95.40	73.20	56.30	26.40	5.60
139	8, 9, 12, 14, 15	Milwaukee, Wis	2.669	99.6	40.2	1.19	......	......	100.00	90.41	61.58	45.65	22.34	9.18
145	8, 9, 12, 14, 15	La Crosse, Wis	2.512	95.8	39.0	2.60	......	......	99.88	99.19	78.71	59.32	29.65	13.23
147	8, 9, 11, 12, 14, 15, 24	Minnesota City, Minn	2.490	100.4	36.4	2.96	......	......	100.00	95.88	84.57	76.39	52.16	21.62
148	8, 9, 12, 14, 15	St. Paul, Minn	2.571	104.7	34.1	1.85	......	......	......	100.00	95.59	84.26	58.64	37.52
150	8, 9, 12, 13, 14, 15, 31	Minneapolis, Minn	2.525	98.9	37.4	2.12	......	......	100.00	95.88	84.57	76.39	52.16	21.62

152	8, 9, 12, 14, 15	Mankato, Minn.	2.543	99.9	37.3	2.34			99.59	92.91	71.25	57.97	27.88	13.59
160	8, 9, 12, 13, 14, 15	Dubuque, Iowa	2.631	99.4	39.8	1.66			99.84	95.34	80.36	66.84	40.19	20.00
163	8, 9, 12, 14, 15	Bettendorf, Iowa	2.552	100.25	37.3	1.38			99.57	95.38	79.45	71.16	50.91	26.60
166	9, 11, 12, 14, 15	Stone City, Iowa	2.166	92.7	33.4	7.26			99.48	94.99	75.33	64.25	48.63	34.23
169	8, 9, 12, 14, 15	Le Claire, Iowa	2.458	98.0	36.5	3.31			99.81	86.15	62.27	53.04	40.96	29.38
172	8, 9, 12	Ottumwa, Iowa	2.633	98.2	39.6	1.02			99.98	95.38	79.68	65.18	29.31	13.21
210	8, 9, 12, 13, 14, 15, 31	Chockee, Ind. Ter.	2.558	102.8	34.6		97.97	94.25	90.24	85.14	74.29	67.48	53.88	36.67
230	17			[c]73.9	51.4						100.00	99.30	97.0	55.5
251	8, 9, 10, 11, 12, 13, 14, 15, 31	Ludlow Falls, Ohio	2.666	85.4	48.6					99.94	98.02	89.54	31.90	12.03
307	8, 9, 10, 12, 13, 14, 15, 31	Joilet, Ill.	2.621	89.2	15.4				100.00	99.78	90.51	74.81	40.00	5.98
388	8, 9, 13, 14, 15, 23, 35	Porto Bello, C. Z.	2.599	102.1	36.9	2.05	98.20	95.72	89.16	80.73	58.46	46.98	30.46	18.92
500	8, 14, 15, 16, 17, 22, 35	St. Louis, Mo.	2.489	97.7	37.1					100.00	99.37	96.04	60.86	28.71
451	33			89.4		.37					99.60	97.08	64.47	20.27
199	37													
206	34													
221	18, 34													
220	36		2.635	78.8	48.0	1.10								
Gravel:														
14	12, 14, 15, 16	St. Claire River, Mich.	2.660	111.2	33.2	1.65		99.19	99.00	98.50	98.00	97.00	90.75	45.50
15	12, 14, 15, 16	Cleveland, Ohio	2.680	127.5	23.0		98.50	96.64	95.76	94.82	92.94	90.50	81.19	62.94
22	8, 9, 12, 14, 15, 16	Rockton, Ill.	2.614	118.2	27.5	1.18			100.00	96.62	84.73	74.71	47.17	18.94
23	8, 9, 12, 14, 15, 16	Beloit, Wis.	2.611	120.8	26.4	1.21			99.89	99.41	95.75	86.00	45.56	28.75
24	8, 9, 11, 12, 14, 15, 16, 31	Jonesville, Wis.	2.633	118.4	27.7	1.35			100.00	96.05	83.47	74.89	50.41	21.79
25	8, 9, 12, 14, 15, 16	La Crescent, Minn.	2.658	117.9	28.6	.53			99.62	99.20	96.12	92.97	84.35	73.81
26	8, 9, 12, 14, 15, 16	Wabasha, Minn.	2.633	120.1	26.9				99.72	99.31	95.77	91.71	81.10	60.39
28	13, 14, 31	Fort Worth, Tex.	2.637	118.3	27.7	1.40	99.88	98.65	97.71	96.23	90.04	85.58	74.00	61.31
28a	10, 11, 14, 15	do	2.529	94.7	39.8	2.52								
35	8, 9, 10, 11, 12, 13, 14, 15, 31	Louisville, Ky.	2.597	111.7	31.0	.61			99.91	97.37	82.38	69.16	37.48	9.42
36	8, 9, 10, 11, 12, 13, 14, 31	do	2.552	105.9	33.4				99.60	95.60	77.50	64.90	36.40	
37	8, 9, 10, 14, 15, 31	Colfax, Iowa	2.396	90.2	39.7	3.18			99.89	99.64	96.01	91.21	74.13	53.40
39	8, 9, 12, 13, 14, 15, 18, 20, 31, 34, 36	St. Louis, Mo.	2.446	[d]100.2	36.9				100.00	99.81	96.81	91.31	68.25	36.13
501	8, 14, 15, 16, 17, 22, 29, 35	Drake, Mo.	2.450	102.4	33.0					100.00	98.50	95.20	79.30	43.00
502	19	New Jersey		93.6					100.00	99.63	91.94	80.50	40.13	7.88

[a] Passing 3-inch screen=96.3.
[b] Three inches=100, 2¾ inches=99.43, 2½ inches=97.90, 2¼ inches=93.28.
[c] Weight per cubic foot with ¼-inch material screened out.
[d] Weight per cubic foot=95.4 pounds with ¼-inch particles screened out.

TABLE 1a—Continued

Physical Properties of Aggregates—Continued

PIT AND CRUSHER RUN MATERIAL—Continued

Aggregate, Lab. No.	Results of tests in tables—	Location	Specific gravity	Weight per cubic foot (pounds)	Per cent voids computed	Per cent absorption	Granular analyses—per cent passing screen— 2-inch	1¾-inch	1½-inch	1¼-inch	1-inch	¾-inch	½-inch	¼-inch
Gravel—Con.														
503	19	Gorgona, C. Z.		121.5				100.00	99.94	95.92	88.12	82.46	67.69	48.30
504	28	Washington, D. C., Potomac River.	2.680	109.0	34.9				98.25		90.25	81.75	66.65	30.75
513	24	Cowe Bay	2.609	102.9	36.7		100.00	99.38	97.15	94.04	84.17	78.66	64.78	28.82
53	38	Shoshone, Wyo	2.558	119.2	25.3		99.43	98.13	95.91	92.74	84.50	79.59	64.48	56.86
54	33, 35		2.446	89.96	41.0	1.35	100.00	99.40	99.30	98.90	94.80	89.30	66.75	11.25
526	26	Chagres River, C. Z.	2.780	130.5	24.8		99.3		91.3		78.5	70.0	56.3	38.5
527 [a]	26, 27	do	2.810	113.5	35.4		94.8		87.0		65.0	50.8	33.0	12.0
514	25, 34	Louisville, Ky	2.597	111.7	31.0	.01			99.9	97.4	82.4	69.2	37.5	
516	25, 34	do	2.552	105.9	33.4	.02			99.6	95.6	77.5	64.9	36.3	
55	32													
Cinders: 507	8, 14, 15, 16, 17, 22, 35, 36	St. Louis, Mo	1.750							100.00	96.50	93.23	97.06	21.58

[a] Same as No. 526, except large portion of material smaller than ¼-inch screened out.

MATERIAL PASSING ¼-INCH SCREEN

Aggregate Lab. No.	Specific gravity	Weight per cubic foot (pounds)	Per cent voids computed	Per cent absorption	Granular analyses—per cent passing sieve No.— 6	10	20	30	40	50	80	100	200
Granite:													
175b	2.546			1.06		42.78	27.45	22.04	13.81	16.20	13.07	11.53	8.00
312b						32.42	23.06	19.14	16.12	14.34	11.40	9.73	7.19
449b					47.02	28.90	18.28	14.52	12.08	10.59	7.89	6.46	4.00

Trap rock:													
505b					1.93	1.57	1.42	1.34	1.24	1.14	.93	.80	.50
506b						49.90	29.70	23.81	18.25	15.79	10.68	9.22	
450b					87.29	74.24	60.74	53.22	47.09	42.85	34.60	29.89	20.79
Limestone:													
30b	2.710		38.9			93.50							
31b						96.00							
128b	2.592			3.05		63.54	48.47	43.60	40.12	36.50	30.50	25.71	17.86
133b	2.694			1.56		38.60	24.70	21.90	20.60	19.40	17.40	15.80	10.20
136b	2.709			1.09		47.27	36.69	32.97	29.38	26.54	22.48	19.56	13.23
139b	2.705			1.18		53.70	32.60	26.00	22.80	20.30	17.80	16.60	13.60
145b	2.566			3.32		39.59	28.06	26.30	25.42	24.66	23.49	22.25	14.06
147b	2.619			2.61		44.74	34.22	32.51	31.46	30.35	27.52	24.45	16.03
148b	2.504			3.52		47.89	29.17	23.83	21.00	18.41	15.44	13.55	8.47
150b	2.558			2.65		26.38	12.86	10.89	9.89	9.12	8.12	7.53	5.60
152b	2.635			1.91		36.50	29.01	27.09	25.08	22.24	17.14	14.27	9.28
160b	2.710			1.23		39.40	25.00	21.70	19.50	17.40	14.00	12.00	7.70
163b	2.591			2.06		38.27	21.77	17.99	15.80	13.90	11.54	10.09	7.89
166b	2.393			6.37		68.65	54.16	48.47	44.96	41.77	37.84	35.38	28.39
169b	2.518					41.02	24.32	21.14	19.51	18.49	17.21	16.40	13.02
172b	2.574			1.99		45.49	29.54	24.54	20.86	17.81	14.10	12.18	7.63
210b	2.466			2.93		48.05	32.48	26.50	22.85	20.81	17.63	15.92	12.18
251b		104.6				63.08	51.45	47.34	44.71	42.99	39.68	37.37	27.82
307b		94.4				20.81	17.91	17.13	16.52	16.17	15.48	15.01	13.20
388b	2.575			2.84		53.04	37.33	30.68	25.86	22.77	17.42	14.50	9.25
500b						41.13	30.44	24.23	19.00	14.22	10.14	6.44	2.96
220b	2.546					27.8	16.8	14.60	12.70	11.70	9.80	8.90	6.90
Gravel:													
14b		117.8	30.7			55.34	55.08						
15b		118.9	27.9										
22b	2.612			1.27		43.19	24.65	13.09	4.24	1.35	.71	.55	.38
23b	2.623			1.13		68.26	57.03	46.85	32.39	13.25	2.91	1.80	.97
24b	2.609			1.38		52.99	36.06	25.36	14.69	6.97	3.01	2.35	1.53
25b	2.637			.68		79.56	59.51	34.86	13.17	3.37	.87	.60	.35
26b						59.24	34.42	12.74	10.15	4.60	2.38	1.62	.71

TABLE 1a—Continued

Physical Properties of Aggregates—Continued

MATERIAL PASSING ¼-INCH SCREEN—Continued

Aggregate Lab. No.	Specific gravity	Weight per cubic foot (pounds)	Per cent voids computed	Per cent absorption	Granular analyses—per cent passing sieve No.—								
					6	10	20	30	40	50	80	100	200
Gravel—Continued													
28b						68.30	53.27	42.94	27.68	15.57	4.17	1.97	0.76
28ab		108.4				70.93	56.76	46.07	20.69	18.11	5.79	3.13	1.43
35b		100.0											
36b		100.8											
37b	2.547	105.2	33.7	1.46		63.45	45.40	33.67	23.85	17.71	7.72	5.84	4.45
39b	2.475		41.7	2.43		16.86	5.22	3.74	2.34	1.18	.68	.60	.43
501b						.95							
502b					4.19	3.49	3.04	2.78	2.51	2.26	1.73	1.41	.88
503b		109.1			36.90	29.12	22.63	18.08	13.37	9.93	5.22	3.52	1.80
513b					13.25	5.41	2.93	2.27	1.78	1.44	1.07	.89	.57
53b					86.12	78.48	69.93	60.67	47.67	37.56	22.01	16.16	8.76
54b					23.76	4.70	1.27	.97	.78	.57	.42	.37	.25
514b						82.16	73.49	65.02	45.82	19.86	1.74	.61	.22
516b						85.94	71.61	58.05	33.53	9.34	1.42	.87	.59
Cinders: 507b						50.60	36.56	27.33	20.23	14.26	9.46	5.59	2.35

TABLE 2

Compressive Strength of Portland Cement Mortars, Showing Effect of Variation in the Proportions of Cement to Fine Aggregate and Variation in Consistency of Mixture

[All results are the average of 3 or more tests of 8 by 16 inch cylinders]

Materials.	Proportion by volume 1:2 (ultimate stress, lbs. per sq. in.)				Proportion by volume 1:3 (ultimate stress, lbs. per sq. in.)						Proportion by volume 1:4 (ultimate stress, lbs. per sq. in.)						Proportion by volume 1:8 (ultimate stress, lbs. per sq. in.)			
	Per cent mixing water	28 da.	3 mo.	6 mo.	Per cent mixing water	7 da.	28 da.	3 mo.	6 mo.	1 yr.	Per cent mixing water	7 da.	28 da.	3 mo.	6 mo.	1 yr.	Per cent mixing water	28 da.	3 mo.	6 mo.
Typical Portland cement and sand 181	[a] 6.5	917	1374	1595	......	......	......	......	......	......	[a] 5.5	......	751	929	1074	......	[a] 4.5	302	433	506
	[b] 9.0	2194	2726	2866	......	......	......	......	......	......	......	......	1137	1670	1584	......	[b] 6.5	589	828	872
	[c] 10.5	3416	3180	3512	......	......	......	......	......	......	......	......	1854	2286	2342	......	[c] 8.0	545	900	838
Typical Portland cement and sand 186	......	......	......	......	13.3	......	1290	2063	2450	......	12.8	......	838	1346	1425	......	......	......	......	......
Typical Portland cement and limestone screenings	......	......	......	......	17.0	1808	2766	3600	3792	4275	16.0	1317	2041	2530	3017	3308	......	......	......	......

[a] Dry consistency. [b] Moist consistency. [c] Plastic consistency.

TABLE 3

Yield Point, Modulus of Elasticity, and Compressive Strength of Portland Cement Mortars of Plastic Consistency

[All results are the average of 3 or more tests of 8 by 16 inch cylinders. Sand 183]

Proportions by volume cement: sand	Per cent water	Weight per cubic foot (pounds)	Age when tested, 4 weeks				Age when tested, 13 weeks			
			Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)	Range (pounds)	Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)	Range. (pounds)
1:1	16.6	137	1834	4 243 000	5613	1580	2600	4 153 000	6739	1670
1:2	14.5	134	....	....	3070	290	1833	4 673 000	4560	1650
1:4	15.1	131	400	2 120 000	1432	160	700	2 200 000	1663	370

TABLE 4

Compressive Strength of Portland Cement Mortars Made With a Large Number of Different Aggregates, Showing Relation Between "Density" (Solidity Ratio) and Strength

[All results are the average of three or more tests of 2-inch cubes]

Materials, Lab. No.	"Density" (solidity[a] ratio) of mortar	Per cent mixing water for plastic consistency	Proportion by volume, 1 part cement to 3 parts aggregate (ultimate stress, lbs. per sq. in.)					Per cent mixing water for plastic consistency	Proportion by volume, 1 part cement to 4 parts aggregate (ultimate stress, lbs. per sq. in.)				
			7 days	28 days	3 months	6 months	1 year		7 days	28 days	3 months	6 months	1 year
Sand:													
161	0.808	8.9	3223	5011	6113	6105	8000	8.3	1852	3044	4457	4133	5293
177	.794	8.9	3570	5169	5108	6200	6492	8.3	2093	3157	3725	5992	4850
176	.789	8.9	4247	5600	5708	6719	7750	8.3	2404	2895	4558	5183	4800
166	.769	8.9	2889	3494	5557	[b] 2934	5858	8.3	1419	2612	3225	2645	4050
163	.766	8.9	2686	4099	3236	4225	4971	8.3	1709	2568	2741	3208	3912
165	.763	8.9	2444	5489	6000	7554	7400	8.3	1694	3864	4108	5193	4515
173	.760	8.9	3228	5671	5525	7108	6742	8.3	2376	3679	4000	4617	4754
159	.756	8.9	1722	3426	4724	5360	5725	8.3	1050	2062	2582	3088	3775
170	.754	8.9	3175	5582	5899	7182	6737	8.3	2863	4435	4432	5492	4308
160	.752	8.9	2000	3731	4857	5280	6135	8.3	1161	2609	3549	3867	4440
162	.752	8.9	2202	2496	4500	4572	[b] 1887	8.3	1397	2036	3147	3614	[b] 2130
167	.743	8.9	1687	2869	4462	4639	5817	8.3	1092	1877	2340	2689	3792
158	.742	8.9	1199	2150	3539	3677	4275	8.3	866	1450	2430	2825	3033
169	.738	8.9	2431	4245	6245	6125	6792	8.3	1888	2839	4028	3825	4300
175	.735	8.9	1563	3086	4012	3667	4476	8.3	1330	2081	2038	3067	3142
171	.733	8.9	1906	3159	3536	4075	3954	8.3	1371	1939	2763	2450	3250
164	.730	8.9	1558	3415	4949	5733	5675	8.3	1098	2209	3449	3333	4317
168	.730	8.9	2094	5289	5692	5067	5658	8.3	2034	3811	4288	4917	4825
179	.709	11.5	2317	4100	5570	4958	....	11.0	1358	2395	3780	3608	....
174	.704	8.9	1908	3112	3952	4742	4766	8.3	1321	2339	2612	3333	3512

[a] See p. 12.

[b] No explanation can be offered for the low value.

TABLE 4—Continued

Compressive Strength of Portland Cement Mortars Made With a Large Number of Different Aggregates, Showing Relation Between "Density" (Solidity Ratio) and Strength—Continued

Materials, Lab. No.	"Density" (solidity ratio) of mortar	Per cent mixing water for plastic consistency	Proportion by volume, 1 part cement to 3 parts aggregate (ultimate stress, lbs. per sq. in.)					Per cent mixing water for plastic consistency	Proportion by volume, 1 part cement to 4 parts aggregate (ultimate stress, lbs. per sq. in.)				
			7 days	28 days	3 months	6 months	1 year		7 days	28 days	3 months	6 months	1 year
Sand—Continued													
178	0.700	8.9	1548	2249	2713	2892	3333	8.3	1071	1238	1853	1975	2367
172	.676	8.9	1262	1898	2033	2633	2729	8.3	954	1352	1554	1833	1958
191			1175	2004					812	1300			
184	.687	11.5	2017	2758				11.0	1217	1867			
185	.637	16.0	1033	1858				15.5	658	1183			
Gravel screenings:													
311	.796	8.9	4634	6268	6400	7825	8817	8.3	2503	3800	4175	4533	4533
309	.791	8.9	4536	5346	6179	8567	9121	8.3	4050	5218	5779	6342	7433
312	.782	8.9	3590	5212	5250	6892	7900	8.3	2717	3842	4600	4975	6150
307	.774	8.9	3850	4329	7133	6325	6379	8.3	1504	3287	3766	a 1687	4342
306	.772	8.9	3106	4238	7026	6397	7025	8.3	2459	3874	5033	5871	6592
301	.771	9.1	3341	5532	6802	7466	7185	8.4	1563	3909	3918	4990	3913
302	.763	9.1	4447	6093	7384	8074	9267	8.4	1899	3481	4746	5012	5067
304	.759	8.9	2398	3896	6098	5570	7192	8.3	1440	2743	4589	4775	4575
305	.756	8.9	3194	4551	6054	6873	7657	8.3	2296	3420	4179	5748	5632
310	.749	8.9	2303	4146	4553	5433	5004	8.3	1411	1832	2607	3275	3062
308	.741	8.9	2484	2519	3206	6825	a 2842	8.3	688	1405	3762	2075	2275
303		8.9	1932	3242	3970	4654	4742	8.3	1423	2616	2977	3233	4043
Stone screenings:													
408	.774	8.9	2841	4208	5514	6307	5571	8.3	1382	2751	3358	4612	5892
410	.763	8.9	2510	3546	4717	7394	6805	8.3	764	2019	2352	3009	3268
406	.760	8 9	3571	6264	7086	8048	8859	8.3	1639	2971	4633	5342	5524

414	.757	8.9	2875	4617	5722	6042	6950	8.3	2051	2681	4092	4576	4442
407	.756	8.9	1813	2798	4433	5279	5402	8.3	904	1648	2303	2352	3192
404	.755	8.9	3408	3639	6342	8644	7805	8.3	1677	3439	3118	4092	4901
419	.753	8.9	2293	3762	4961	5459	5748	8.3	1704	2624	3610	4660	5842
425	.752	8.9	3346	4277	4850	5417	6692	8.3	2894	3112	4350	4875	4617
409	.752	8.9	2385	4187	5262	5982	5528	8.3	1399	2579	3568	4089	4592
418	.746	8.9	2221	3177	4813	6221	6542	8.3	1546	2451	3262	4154	4542
405	.745	8.9	2408	3952	4367	4954	6195	8.3	1370	1842	2008	2488	4292
413	.743	8.9	2550	4409	5097	5394	5842	8.3	1234	2221	3204	6200	3900
401	.740	8.9	2554	3717	4848	5663	[a] 1949	8.3	1949	2233	3437	3703	4625
416	.740	8.9	1805	3571	5282	4972	6807	8.3	1363	2301	3056	3642	4800
423	.737	8.9	1563	2876	3674	4362	5650	8.3	1380	2355	3097	2910	4217
403	.733	8.9	2937	4683	5578	6500	6016	8.3	2444	3622	4384	5029	5106
412	.733	8.9	2775	4498	6280	6193	6725	8.3	1615	2929	3748	4138	5800
415	.726	8.9	1747	3037	5387	4681	5652	8.3	916	954	1279	1800	1217
402	.721	8.9	2466	3316	4410	5251	5457	8.3	1587	2650	3533	4253	4855
422	.719	8.9	2568	4671	6267	7382	8500	8.3	1956	3225	4646	4750	5808
411	.709	8.9	1082	2052	3002	3757	4908	8.3	945	1547	2213	2740	3813
424	.666	8.9	1836	2744	3011	3692	4858	8.3	955	1812	2198	2742	1958
421	.655	8.9	1635	2392	3482	3948	5142	8.3	1188	1838	2662	3396	4125
417	....	8.9	2221	4023	4512	5313	6775	8.3	1051	5157	3115	3750	3383
420	....	8.9	2586	4079	5350	4998	6375	8.3	1946	1877	4239	3719	5383
Slag sand: 501	....	8.9	770	1030	1090	2330	2960	8.3	500	720	540	1220	1870

[a] No explanation can be offered for the low value.

TABLE 5

Compressive Strength of Portland Cement Mortars, Showing Relation Between Natural and Standard Ottawa Sand

[The results are arranged in the order of increasing fineness of sands, No. 3 being coarsest and No. 157 the finest. All results are the average of three tests of 2-inch cubes]

Sand, Lab. No.	Per cent water	"Density" (solidity ratio) *a* of mortar	Compressive strength (lbs. per sq. in.)						Ratio of A to B in per cent		
			Natural sand 1:3 (A)			Standard Ottawa sand 1:3 (B)					
			1 week	4 weeks	13 weeks	1 week	4 weeks	13 weeks	1 week	4 weeks	13 weeks
3	11.3	0.746	2503	4225	5325	1787	2782	3583	140	152	145
4	11.3	.762	2815	4812	5903	1423	2692	3387	198	179	176
6	9.6	.766	3680	5275	6405	1963	3227	4005	187	160	160
7	12.3	.757	2437	3753	4400	1787	2782	3583	136	135	123
10	14.5	.760	1988	3043	3962	1419	2363	3385	140	129	117
12	11.3	.721	2032	3590	4552	1713	2487	3403	119	144	134
13	11.3	.731	1883	3515	4998	1419	2363	3385	133	149	148
14	12.5	.721	1838	3512	4438	1683	2887	3612	109	122	123
17	13.8	.767	2272	3230	5067	1963	3227	4005	116	100	127
18	11.4	.757	2772	4507	5177	1423	2692	3387	195	167	153
19	10.4	.699	2670	5048	6883	1423	2692	3387	188	187	203
20	11.3	.729	2288	3532	4865	1713	2487	3403	134	142	143
21	11.3	.742	2203	3837	4550	1419	2363	3385	155	162	134
22	11.3	.729	2318	3457	4695	1419	2363	3385	163	146	139
23	11.3	.737	1997	3213	3977	1713	2487	3403	117	129	117
24	11.3	.746	2542	3788	4962	1713	2487	3403	148	152	146
25	11.9	.740	2680	4212	5755	1953	3125	3750	137	135	153
26	11.9	.699	1465	2070	2983	1497	2153	3258	98	96	92
27	12.5	.709	1680	3865	5017	1677	2970	3290	100	130	152
29	14.5	.741	1597	2415	3433	1419	2363	3385	113	102	101
30	13.8	.732	1367	2342	3837	1497	2153	3258	91	109	118
31	12.5	.729	1458	2737	3953	1497	2153	3258	97	127	121
32	10.0	.742	3092	5133	6317						

34	12.5	.727	1475	1980	2530	1255	2523	3112	118	78	81
36	9.5	.739	3092	4942	5761						
37	10.5	.736	2925	4817	6254						
39	12.5	.705	1835	3567	4922	1623	2498	3233	113	143	152
40	10.6	.737	2590	3913	5040	1963	3227	4005	132	121	126
42	12.5	.728	1917	2797	3858	1707	2628	3550	112	106	109
44	11.5	.682	2017	2758	3842						
45	10.5		2225	3452	4358	1270	2272	2835	175	152	154
50	11.5	.706	2103	3275	4880	1623	2498	3233	130	131	151
52	15.6	.673	1227	2043	3007	1638	2532	3622	75	81	83
54	11.8	.690	1673	2930	4188	1955	3123	3750	85	94	112
55	13.1	.706	1595	2783	3827	1787	2782	3583	89	100	107
56	14.2	.710	1198	2487	3570	1787	2782	3583	67	89	99
57	15.5	.677	1038	1863	3103	1363	2230	3210	76	84	97
58	13.5	.707	1723	3120	4345	1419	2363	3385	121	132	128
59	15.0	.676	1175	2005	2558						
61	13.5	.735	2113	3638	4308	1683	2887	3612	126	126	119
62	11.9	.640	1605	2810	4168	1497	2153	3258	107	131	128
63	12.5	.687	1502	3072	3935	1423	2692	3387	106	114	116
64	12.0	.721	2200	4083	4492						
65	11.0		1725	2592	3858						
67	15.6	.669	1320	1957	3046	1613	2662	3680	82	74	83
69	12.5	.711	2038	3703	4423	2082	2758	3663	98	134	121
70	17.5	.743	1078	2067	2909	2082	2758	3663	52	75	79
71	12.5	.696	2098	3387	3857	1677	2970	3290	125	114	117
72	14.1	.683	1390	2500	3583	1787	2782	3683	78	90	100
73	12.1	.692	1760	2523	3450	1955	3123	3750	90	81	92
74	12.5	.704	1663	2968	4050	1638	2532	3622	102	117	112
76	13.8	.666	1027	1937	2878	1255	2523	3112	82	77	93
77	16.0	.641	1033	1858	2192						
78	12.0	.693	1675	2508	3208						
79	11.5	.708	2000	3406	4058						
80	12.0	.710	1725	3100	4075						
81	11.0	.722	2330	3518	4525	1713	2487	3403	136	141	133

[a] See p. 12.

TABLE 5—Continued

Compressive Strength of Portland Cement Mortars, Showing Relation Between Natural and Standard Ottawa Sand—Continued

Sand, Lab. No.	Per cent water	"Density" (solidity ratio) of mortar	Compressive strength (lbs. per sq. in.)						Ratio of A to B in per cent		
			Natural sand 1:3 (A)			Standard Ottawa sand 1:3 (B)					
			1 week	4 weeks	13 weeks	1 week	4 weeks	13 weeks	1 week	4 weeks	13 weeks
82	10.8	0.719	1745	2785	3875	1270	2272	2835	137	123	136
84	12.5	.694	1060	1770	2695	1255	2523	3112	84	70	68
85	12.5	.657	1617	2815	2982	1613	2662	3680	100	105	81
86	15.6	.684	1793	2852	3380	1677	2990	3290	107	95	103
87	13.4	.689	1625	2882	3687	1526	2708	3340	106	106	110
88	13.8	.679	1607	2710	2975	1526	2708	3340	105	100	89
89	13.3	.664	1368	2087	3075	1955	3123	3750	70	67	82
90	13.3	.691	1845	3197	3290	1677	2970	3290	110	108	100
91	9.5	.738	2592	4408	5054						
92	10.0	.688	2282	4892	5058						
93	11.0	.695	1583	2758	3444						
94	11.4	.738	1590	2142	3335	1270	2272	2835	125	94	118
95	13.6	.670	1410	2428	3217	1526	2708	3340	92	90	96
98	12.5	.686	1383	2432	3550	1683	2887	3612	94	84	98
99	15.6	.678	1315	2370	3380	1683	2887	3612	78	82	94
101	12.2	.679	1137	2073	2612	1497	2153	3258	76	96	80
102	14.4	.663	1088	1925	3320	1963	3227	4005	55	60	83
103	14.5	.669	1058	2100	2738	1963	3227	4005	54	65	68
104	10.5	.712	2042	3875	4017						
106	12.2	.693	1417	2548	3343	1526	2708	3340	93	94	100
107	12.5	.681	852	1620	2472	1270	2272	2835	67	71	87
108	16.3	.608	585	968	1635	1255	2523	3112	47	38	53
109	15.5	.660	903	2118	2867	1423	2692	3387	63	79	85
110	15.5	.682	692	998	1907	1419	2363	3385	49	42	66

110	13.1	.660	888	1535	2403	1270	2272	2835	70	68	85
113	15.6	.665	1105	1663	2147	1613	2662	3680	68	62	58
114	15.2	.645	1313	2070	3353	1623	2498	3233	81	83	104
115	15.6	.651	1130	2113	3187	2082	2758	3663	54	77	87
116	15.3	.662	1077	1938	3098	1255	2523	3112	86	77	100
119	14.5	.644	703	1092	1700	1363	2230	2210	52	49	53
120	13.5	.686	1557	2532	8018	1707	2628	3550	91	96	85
124	15.6	.632	733	1453	2160	1623	2498	3233	45	58	67
125	11.0	.698	1717	3017	4017	......	......	......	......	......	......
126	12.5	.684	1617	3050	3771	......	......	......	......	......	......
127	13.1	.658	1328	2060	3100	1953	3125	3750	68	66	83
129	12.5	.704	1505	2355	3400	1683	2887	3612	89	81	94
130	15.6	.633	737	1418	2467	1497	2153	3258	49	66	76
131	14.5	.647	615	1122	1830	1363	2230	3210	45	50	57
132	15.6	.628	835	1558	2223	1613	2662	3680	51	59	60
137	15.6	.633	692	1313	1850	1526	2708	3340	45	49	55
140	18.8	.617	848	1760	2150	1423	2692	3387	60	65	63
142	18.3	.607	418	895	1538	1363	2230	3210	31	40	48
144	14.4	.631	510	1073	1763	1499	2153	3358	34	50	53
145	25.0	.536	388	785	1085	1638	2532	3622	24	31	30
146	18.8	.618	490	1035	1577	1363	2230	3210	36	46	49
148	16.6	.628	598	1268	1818	1363	2230	3210	44	57	57
149	18.8	.647	485	797	1347	1255	2523	3112	39	32	43
150	18.7	.599	285	643	1133	1255	2523	3112	31	25	36
151	21.7	.606	548	1052	1665	1363	2230	3210	40	47	52
152	15.5	.634	760	1590	2333	1423	2692	3387	53	59	69
154	15.6	.631	1038	1747	2317	1677	2970	3290	62	59	70
156	20.6	.596	407	572	983	1255	2523	3112	32	23	32
157	15.0	.628	578	1168	1825	1270	2272	2835	46	51	64

TABLE 6

Transverse and Compressive Strength of Mortar Building Blocks and Corresponding 8 by 16 Inch Cylinders (Ultimate Strength in Pounds per Square Inch)

[Block tests, average of 3; cylinder tests, average of 2. Sand, 183]

Proportion (by volume), consistency, and type of block	Age when tested, 28 days			Age when tested, 90 days			Age when tested, 180 days		
	Block		Cylinder	Block		Cylinder	Block		Cylinder
	Transverse	Compression		Transverse	Compression		Transverse	Compression	
1 to 2:									
Dry, 6½ per cent—									
A [a]	149	779	894	214	1000	1261	190	860	1267
B	170	1005	632	241	1359	1699	348	1778	2017
C	367	1426	1245	419	1249	1363	447	1446	1698
D	213	1038	960	285	1260	1490	280	1404	1380
E	151	1130	853	291	1396	1057	296	1362	1611
Moist, 9 per cent—									
A	204	916	1882	329	1122	2632	318	1270	2508
B	260	1515	1557	317	1630	2824	336	1980	2894
C	323	1636	2167	401	2017	2609	488	1782	2656
D	316	1326	2456	398	2197	....	440	2083	....
E	359	1535	2905	384	1720	2840	391	1738	3406
Plastic, 10½ per cent—									
A	361	1288	(b)	380	1702	(b)	360	1940	(b)
B	315	1852	3873	396	2101	(b)	439	1978	(b)
C	480	1833	2752	509	1845	3180	561	1768	3110
D	439	2210	(b)	540	2272	(b)	644	2306	3914
E	413	1869	3624	429	1841	(b)	445	1522	(b)

1 to 4:									
Dry, 5½ per cent—									
A	79	311	384	83	434	780	111	500	793
B	90	447	923	172	790	1050	139	651	1257
C	178	919	790	231	983	1169	225	872	1250
D	144	740	692	217	600	965	221	771	994
E	113	608	969	131	626	682	146	714	....
Moist, 8 per cent—									
A	176	900	965	245	1153	1668	219	1006	1874
B	208	1270	1093	247	1641	1439	267	1531	1671
C	218	1081	1015	265	1354	1924	302	1170	1751
D	241	1578	1330	327	1157	1435	363	1834	1910
E	231	1132	1283	286	1251	1885	293	1313	1627
Plastic, 9 per cent—									
A	214	817	1787	269	1169	2165	280	1173	2156
B	210	1727	2145	266	1661	2488	300	1960	2591
C	298	1560	2011	383	1751	2361	362	1320	2394
D	305	1770	1754	346	1570	2291	351	2190	2412
E	209	1112	1573	248	1335	2125	259	1373	2158
1 to 8:									
Dry, 4½ per cent—									
A	48	164	255	63	183	432	88	214	364
B	36	177	311	60	238	453	69	241	463
C	70	222	377	91	277	452	105	304	622
D	57	250	276	94	271	403	80	262	565
E	38	195	291	55	196	426	57	187	514
Moist, 6½ per cent—									
A	88	356	563	119	385	915	147	519	900
B	91	473	519	132	851	873	121	822	892
C	125	588	695	168	526	913	208	758	863
D	119	568	566	162	524	761	175	742	808
E	104	447	600	150	528	878	136	607	895

[a] See Fig. 9 for design of block.

[b] Exceeded capacity of testing machine.

TABLE 6—Continued

Transverse and Compressive Strength of Mortar Building Blocks and Corresponding 8 by 16 Inch Cylinders (Ultimate Strength in Pounds per Square Inch)—Continued

Proportion (by volume), consistency, and type of block	Age when tested, 28 days			Age when tested, 90 days			Age when tested, 180 days		
	Block		Cylinder	Block		Cylinder	Block		Cylinder
	Trans-verse	Com-pression		Trans-verse	Com-pression		Trans-verse	Com-pression	
I to 8—Continued									
Plastic, 8 per cent—									
A	78	379	562	154	416	948	187	590	814
B	90	597	669	125	895	1037	140	1052	926
C	165	579	559	194	756	874	192	920	810
D	113	501	483	188	699	731	175	836	829
E	114	471	453	154	630	909	165	561	810

TABLE 7

Tensile Strength of Portland Cement Mortars, Showing Relation Between Natural and Standard Ottawa Sand

[The results are arranged in the order of increasing fineness of sands, No. 1 being the coarsest and No. 157 the finest. All results are the average of 3 tests]

Sand, Lab. No.	Per cent water	"Density" (solidity ratio) [a] of mortar	Tensile strength (lbs. per sq. in.)						Ratio of A to B in per cent		
			Natural sand 1: 3 (A)			Standard Ottawa sand 1: 3 (B)					
			1 week	4 weeks	13 weeks	1 week	4 weeks	13 weeks	1 week	4 weeks	13 weeks
1	10.4	0.758	267	325	363	210	280	367	127	116	99
2	10.4	.783	339	380	420	239	297	376	142	128	112
3	11.3	.746	285	406	501	191	309	353	149	131	142
4	11.3	.762	182	402	502	239	297	376	76	135	134
5	11.9	.718	265	328	423	225	282	370	118	116	114
6	9.6	.766	242	316	333	201	298	323	120	106	103
7	12.3	.757	253	372	436	191	309	353	132	120	124
8	13.5	.749	260	358	432	193	271	345	135	132	125
9	9.4	.736	227	295	385	225	282	370	101	105	104
10	14.5	.760	297	373	426	229	291	385	130	130	111
11	10.3	.760	313	370	440	221	293	396	142	126	111
12	11.3	.721	240	283	318	201	298	223	119	95	98
13	11.3	.731	286	363	438	255	341	360	112	106	122
14	12.5	.721	199	281	313	222	277	350	90	102	89
15	12.5	.719	206	279	352	222	377	350	93	101	101
16	12.5	.728	301	372	414	193	271	345	156	137	120
17	13.8	.767	268	345	350	201	298	323	133	116	108
18	11.4	.757	274	393	451	210	280	367	131	140	123
19	10.4	.699	247	306	436	339	297	276	103	103	116
20	11.3	.729	220	270	312	201	398	323	109	91	97
21	11.3	.714	344	413	444	229	291	385	151	142	115

[a] See p. 12.

TABLE 7—Continued

Tensile Strength of Portland Cement Mortars, Showing Relation Between Natural and Standard Ottawa Sand—Continued

Sand, Lab. No.	Per cent water	"Density" (solidity ratio) of mortar	Tensile strength (lbs. per sq. in.)						Ratio of A to B in per cent		
			Natural sand 1:3 (A)			Standard Ottawa sand 1:3 (B)					
			1 week	4 weeks	13 weeks	1 week	4 weeks	13 weeks	1 week	4 weeks	13 weeks
22	11.3	0.729	288	364	446	255	341	360	113	107	124
23	11.3	.737	227	271	227	201	298	323	113	91	101
24	11.3	.746	252	263	226	201	298	323	125	88	101
25	11.9	.740	278	403	468	231	317	339	120	127	138
26	11.9	.699	210	265	311	277	395	405	76	67	77
27	12.5	.709	197	260	267	209	306	313	94	85	85
28	12.5	.709	265	361	395	209	306	313	127	118	126
29	14.5	.741	242	328	467	229	291	385	106	113	121
30	13.8	.732	271	356	424	293	389	379	92	92	112
31	12.5	.729	231	329	408	293	389	379	79	85	108
32	10.0	.742	347	456	510						
33	12.5	.697	220	308	396	209	306	313	105	101	127
34	12.5	.727	237	318	369	318	395	407	75	81	91
35	12.5	.706	250	308	365	225	282	370	111	109	99
36	9.5	.739	333	464	532						
37	10.5	.736	319	433	475						
38	15.6	.694	195	268	299	183	258	292	107	104	102
39	12.5	.705	218	309	381	225	282	370	97	109	103
40	10.6	.737	224	275	295	201	298	323	111	92	91
41	13.0	.697	246	314	395	239	297	376	103	106	105
42	12.5	.728	228	303	386	193	271	345	118	112	112
43	12.5	.705	205	241	274	255	241	360	80	71	76
44	11.5	.682	259	292	451						
45	10.5	.647	355	391	267	297	293	401	90	90	97

46	10.7	.715	228	310	387	299	379	421	76	82	92
47	11.3	.715	266	341	394	299	379	421	89	90	94
48	13.5	.686	167	219		187	273		89	80	
49	11.9	.688	187	282		297	393		63	72	
50	11.5	.706	245	257	324	225	282	370	109	91	87
51	12.5	.703	205	271	369	183	258	292	112	105	126
52	15.6	.674	174	255	319	183	258	292	95	98	109
53	12.5	.712	240	315	392	225	282	370	107	112	106
54	11.8	.690	189	281	208	331	217	339	82	89	91
55		.706	207	309	332	191	309	353	108	100	94
56	14.2	.710	315	303	286	191	309	353	113	98	81
57	15.5	.677	163	219	251	192	276	333	85	79	75
58	13.5	.707	276	317	449	229	291	285	121	109	117
59	15.0	.676	219	339	392						
60	12.5	.695	189	384	335	221	293	395	86	97	85
61	13.5	.735	225	317	412	222	277	350	101	114	118
62	11.9	.640	272	343	414	277	395	405	98	87	102
63	12.5	.687	209	255	333	210	380	367	100	91	91
64	12.0	.721	317	425	487						
65	11.0		242	353	380						
66	12.5	.718	230	291	375	176	294	330	131	99	114
67	15.6	.669	175	245	357	180	292	365	97	84	98
68	12.5	.696	216	284	337	225	282	370	96	101	91
69	12.5	.711	207	298	379	209	205	313	99	97	121
70	17.5	.743	148	245	386	209	206	313	71	80	98
71	12.5	.696	201	279	309	209	306	313	96	91	99
72	14.1	.683	177	236	302	190	309	353	93	77	86
73	12.1	.692	184	282	250	231	318	339	80	89	103
74	12.5	.704	184	283	281	183	258	292	100	110	96
75	12.5	.681	181	273	352	176	294	230	103	93	107
76	13.8	.666	217	237		297	393	401	73	60	
77	16.0	.641	147	258	331						
78	12.0	.693	217	336	367						
79	11.5	.708	374	365	434						
80	12.0	.710	359	332	425						

TABLE 7—Continued

Tensile Strength of Portland Cement Mortars, Showing Relation Between Natural and Standard Ottawa Sand—Continued

Sand, Lab. No.	Per cent water	"Density" (solidity ratio) of mortar	Tensile strength (lbs. per sq. in.)						Ratio of A to B in per cent		
			Natural sand 1 : 3 (A)			Standard Ottawa sand 1 : 3 (B)					
			1week	4 weeks	13 weeks	1 week	4 weeks	13 weeks	1 week	4 weeks	13 weeks
81	11.0	0.722	237	268	344	201	298	323	118	90	107
82	10.8	.719	284	363	446	317	383	436	90	95	102
83	14.5	.639	205	296	350	293	389	279	70	75	92
84	12.5	.694	169	296	389	192	276	333	88	107	117
85	12.5	.657	160	201	296	180	292	365	89	69	81
86	15.6	.684	186	284	295	209	306	313	89	93	94
87	13.4	.689	209	275	362	210	297	362	100	93	100
88	13.8	.679	188	283	367	210	297	362	89	95	101
89	13.2	.664	187	251	204	231	317	339	81	79	89
90	13.3	.691	199	317	396	209	306	313	95	104	127
91	9.5	.738	322	425	486						
92	10.0	.688	319	469	512						
93	11.0	.695	230	322	376						
94	11.4	.738	299	268	420	317	383	436	94	96	96
95	13.6	.670	163	255	299	210	297	362	78	86	83
96	15.6	.653	171	271	282	225	282	370	76	96	76
97	11.4	.702	272	259	383	317	383	486	86	94	88
98	12.5	.686	204	275	354	222	277	350	92	99	101
99	15.6	.678	156	243	310	222	277	350	70	88	99
100	14.5	.626	148	213	282	255	341	360	58	62	78
101	12.2	.679	291	358	409	277	395	405	104	91	101
102	14.4	.663	146	257	252	201	298	223	73	86	78
103	14.5	.669	140	219	261	201	298	323	70	73	81
104	10.5	.712	284	394	416						

105	14.0	.657	162	248	316	209	306	313	77	75	101
106	12.2	.693	202	274	226	210	297	363	96	92	90
107	12.5	.681	221	278	311	317	383	436	69	72	71
108	16.3	.608	155	188	260	293	389	379	53	48	68
109	15.5	.660	159	234	312	239	297	376	67	79	83
110	15.5	.682	180	216	281	255	341	360	70	63	78
111	13.1	.660	211	308	376	317	383	436	66	80	86
112	14.3	.630	176	256	299						
113	15.6	.655	108	176	239	180	292	365	60	60	66
114	15.2	.645	158	225	252	225	282	270	70	80	68
115	15.6	.651	147	209	287	209	306	313	70	69	92
116	15.3	.662	204	357	405	397	393	401	69	91	101
117	12.5	.678	177	189	263	221	293	396	80	64	66
118	11.5		211	296	345						
119	14.5	.644	143	159	213	192	276	332	74	58	64
120	13.5	.686	186	275	332	192	271	341	91	101	96
121	14.5	.656	157	236	283	193	241	345	81	87	82
122	13.0	.672	187	237	266	221	293	396	85	81	67
123	13.6	.671	209	206	349	313	364	428	67	79	82
124	15.6	.632	136	183	242	176	294	330	77	62	73
125	11.0	.698	218	318	224						
126	12.5	.684	237	361	436						
127	13.1	.658	201	256	320	231	317	339	87	81	95
128	14.2	.648	197	248	325	313	364	428	63	68	76
129	12.5	.704	185	228	321	221	277	350	83	83	92
130	15.6	.633	161	260	369	293	389	379	55	67	97
131	14.5	.647	149	234	259	255	341	360	59	69	75
132	15.6	.628	135	240	295	180	292	365	75	82	81
133	12.5	.663	180	252		187	273		96	92	
134	13.6	.638	145	231	252	176	294	330	82	79	76
135	11.5	.662	240	290	316	297	393	401	81	74	79
136	18.7	.614	161	227	277	229	291	385	70	77	72
137	15.6	.633	129	204	259	210	297	362	62	68	72
138	16.6	.623	159	233	271	255	341	360	63	67	75
139	19.8	.602	110	184	232	210	280	367	52	66	63

TABLE 7—Continued

Tensile Strength of Portland Cement Mortars, Showing Relation Between Natural and Standard Ottawa Sand—Continued

Sand, Lab. No.	Per cent water	"Density" (solidity ratio) of mortar	Tensile strength (lbs. per sq. in.)						Ratio of A to B in per cent		
			Natural sand 1 : 3 (A)			Standard Ottawa sand 1 : 3 (B)					
			1 week	4 weeks	13 weeks	1 week	4 weeks	13 weeks	1 week	4 weeks	13 weeks
140	18.8	0.617	155	205	277	210	280	367	74	73	76
141	15.0	.658	178	283	319	301	400	444	59	71	72
142	18.3	.607	81	122	204	192	276	333	42	44	61
143	19.5	.643	119	158	259	209	306	313	57	52	83
144	14.4	.631	150	177	237	277	395	405	54	45	58
145	25.0	.536	81	230	203	183	258	292	44	89	70
146	18.8	.618	128	203	279	255	341	360	50	59	78
147	15.8	.624	173	225	313	313	364	428	55	62	73
148	16.6	.628	147	254	306	255	240	360	58	74	85
149	18.8	.647	127	211	271	318	395	407	40	53	67
150	18.7	.599	99	129	186	192	276	333	52	47	58
151	21.7	.606	97	147	204	193	276	333	50	53	61
152	15.5	.634	123	193	208	221	293	296	56	96	53
153	18.8	.614	103	162	194	180	292	365	57	55	53
154	15.6	.631	187	260	295	209	306	315	90	85	94
155	16.5	.621	125	186	238	221	293	396	57	64	60
156	20.7	.596	98	140	191	192	276	333	51	51	57
157	15.0	.628	171	258	296	297	393	401	58	66	74

TABLE 7a

Long-Time Tensile Tests of Neat Portland Cement and Mortars

[Test pieces stored in fresh water until broken. All results average of 4 tests]

NEAT CEMENT BRIQUETTES

Bin	Mixture	Per cent mixing water	Tensile strength (pounds per square inch)																			
			1 day	3 days	7 days	14 days	28 days	8 weeks	13 weeks	26 weeks	39 weeks	1 year	1¼ years	1½ years	2 years	2½ years	3 years	3½ years	4 years	4½ years	5 years	6 years
1	Neat cement	21.5	460	[a]725	711	693	710	711	761	754	721	744	678	699	783	657	596	611	537	641	539	......
2	do	20.5	616	731	754	829	817	916	871	887	915	820	798	804	776	813	775	771	698	658	812	......
3	do	21.5	443	[a]683	710	697	753	733	731	771	718	676	716	755	801	668	669	674	618	697	677	......
4	do	21.0	487	566	716	754	748	689	759	770	720	722	790	740	728	631	705	649	585	606	663	......
5	do	21.0	336	656	643	759	735	732	703	755	770	724	714	712	693	732	631	585	661	689	619	......
6	do	21.0	475	665	665	684	655	785	740	806	811	731	724	733	674	661	726	606	625	586	598	......
7	do	21.5	544	753	712	756	754	757	764	728	765	666	647	664	648	675	620	566	583	554	503	......
8	do	21.0	397	692	715	760	724	708	760	748	767	745	629	757	721	620	579	575	630	555	515	......
9	do	21.0	429	796	699	760	738	750	715	770	750	683	664	731	657	646	761	631	559	674	600	......
10	do	21.5	571	679	671	743	767	713	727	713	732	738	714	660	613	600	574	612	522	642	538	......
11	do	22.0	366	537	595	630	711	680	729	751	649	715	630	628	579	685	618	613	666	526	552	637
12	do	22.0	445	713	700	703	773	744	757	694	701	714	730	770	710	626	733	689	541	659	616	606
	Average	....	464	699	691	731	740	743	751	762	752	723	703	721	699	668	666	632	602	624	603	621

[a] Age 5 days when tested.

TABLE 7a—Continued

Long-Time Tensile Tests of Neat Portland Cement and Mortars—Continued

SAND MORTAR BRIQUETTES

Bin	Mixture	Per cent mixing water	Tensile strength (pounds per square inch)																			
			1 day	3 days	7 days	14 days	28 days	8 weeks	13 weeks	26 weeks	39 weeks	1 year	1¼ years	1½ years	2 years	2½ years	3 years	3½ years	4 years	4½ years	5 years	6 years
1	1 part cement, 3 parts Ottawa sand.	9.0	.....	262	229	379	368	342	451	485	384	412	394	356	342	352	331	318	327	343	336	....
2	do	8.9	.....	272	348	386	403	453	441	471	488	404	366	379	368	374	337	350	330	343	347	....
3	do	9.0	.....	[a]342	336	365	403	448	431	420	416	400	370	380	404	364	325	332	292	333	325	....
4	do	9.0	.....	215	314	318	392	411	415	415	366	391	337	333	287	281	307	282	277	306	245	....
5	do	9.0	.....	304	321	369	384	425	437	459	487	389	394	389	366	383	364	365	354	354	342	....
6	do	9.0	.....	234	337	340	359	424	448	492	490	441	381	397	361	375	373	368	322	319	306	....
7	do	9.1	.....	307	356	388	437	450	449	475	463	405	377	361	366	354	360	324	322	320	332	....
8	do	9.0	.....	308	348	391	419	409	423	467	469	360	378	378	372	335	355	322	321	310	327	....
9	do	9.0	.....	299	345	351	427	430	448	447	461	347	361	379	306	335	304	335	306	321	333	....
10	do	9.0	.....	312	318	396	403	420	442	415	404	409	386	335	363	337	304	330	299	296	329	....
	Average	....	.....	285	325	368	399	421	438	455	445	396	364	368	354	349	336	333	315	324	322	....
11	1 part cement, 3 parts quartz sand.	10.5	.....	145	205	223	274	320	338	374	332	328	341	331	299	306	279	271	272	169	232	255
12	do	10.5	.....	195	275	281	340	339	379	344	312	331	351	333	234	256	265	255	235	216	239	233
	Average	....	.....	170	240	252	307	329	358	359	322	329	346	332	296	231	272	263	253	192	235	244

[a] Age 5 days when tested.

TABLE 8

Yield Point, Modulus of Elasticity, and Compressive Strength of Portland Cement Concretes Made With 37 Different Aggregates

[All results are the average of 3 tests of 8 by 16 inch cylinders unless otherwise noted. All concrete was mixed in the proportion by values of 1 part cement to 2 parts fine aggregate to 4 parts coarse aggregate]

Aggregates		Per cent mixing water of quaking consistency	Weight per cubic foot	Age when tested, 4 weeks			Age when tested, 13 weeks			Age when tested, 26 weeks			Age when tested, 52 weeks		
Coarse, crusher run or bank run	Sand passing ¼-inch screen			Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)	Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)	Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)	Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)
Limestone:															
169	182	7.5	147	967	2 933 000	2343	1233	3 876 000	3413	1167	4 100 000	3752	.....	.....	3789
388	184	8.6	151	.....	.....	2140	633	3 833 000	3009	.....	.....	.....	.....	.....	.....
388	185	8.6	148	.....	.....	1811	666	3 306 000	2559	.....	.....	.....	.....	.....	.....
163	181	8.0	148	633	2 740 000	1887	1067	3 863 000	3437	1033	4 303 000	3331	.....	.....	4555
128	183	6.0	153	950	4 700 000	*a b* 3974	.....	.....	.....	.....	.....	.....	.....	.....	.....
251	183	8.25	152	967	3 576 000	3370	900	4 570 000	3630	1260	4 520 000	4601	.....	.....	.....
160	181	7.5	149	1133	4 243 000	2879	1267	4 620 000	3962	.....	.....	.....	.....	.....	*c* 4981
136	183	7.0	151	1600	4 335 000	*a* 3984	.....	.....	.....	1500	6 980 000	*a* 3999	.....	.....	*a d* 5975
133	183	7.0	152	1700	4 250 000	*e* 3970	.....	.....	.....	1700	4 250 000	*e* 3974+	.....	.....	*a f* 5229
150	181	7.5	150	667	3 073 000	2596	1167	4 080 000	3926	1000	4 680 000	3904	.....	.....	4646
148	181	7.5	148	650	3 605 000	2460	900	3 876 000	3318	633	4 446 000	3779	900	3 876 000	3966
147	181	8.0	147	900	2 193 000	2326	1100	2 433 000	3535	1066	3 883 000	3699	1666	4 280 000	4438
145	181	7.0	150	2300	2 883 000	3702	1600	3 380 000	*a e* 3988	.....	.....	.....	.....	.....	*g* 5537
139	183	7.0	151	1150	4 965 000	*h* 3905	.....	.....	.....	1650	5 340 000	*a e* 4024	.....	.....	*a i* 6549
152	181	8.0	148	700	3 720 000	3678	2300	4 880 000	3207	1033	4 826 000	3811	.....	.....	4693
172	183	8.5	151	1050	3 590 000	2435	1200	3 935 000	3325	.....	.....	.....	.....	.....	.....

a Average of 2 tests.
b Ultimate stress (average of 2 tests): At 78 weeks, 5589; at 104 weeks, 7240.
c Ultimate stress: At 78 weeks, 5505; at 104 weeks, 6150 (1 test only).
d Ultimate stress: At 78 weeks, 7285; at 104 weeks, 7053.
e Exceeded capacity of testing machine.
f Ultimate stress (average of 2 tests): At 78 weeks, 5463; at 104 weeks, 6775.
g Ultimate stress: At 78 weeks, 6377; at 104 weeks, 6716 (average of 4 tests).
h Average of 21 tests.
i Ultimate stress (average of 2 tests): At 78 weeks, 5957; at 104 weeks, 6549.

TABLE 8—Continued

Yield Point, Modulus of Elasticity, and Compressive Strength of Portland Cement Concretes Made With 37 Different Aggregates—Continued

Aggregates		Per cent mixing water of quaking consistency	Weight per cubic foot	Age when tested, 4 weeks			Age when tested, 13 weeks			Age when tested, 26 weeks			Age when tested, 52 weeks		
Coarse, crusher run or bank run	Sand passing ¼-inch screen			Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)	Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)	Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)	Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)
Limestone—Continued															
307	183	10.5	148	.....	.....	2161	.....	.....	*a* 2851	.....	.....	3175	.....	.....	4247
307	(*b*)	11.2	150	.....	.....	*a* 1276	.....	.....	*a* 1737	.....	.....	2137	.....	.....	.....
210	183	9.1	144	467	3 906 000	1776	1167	4 166 000	2777	1400	4 227 000	3032	1800	4 840 000	3810
500	181	10.0	147	800	2 590 000	*c* 2492	1450	3 810 000	*c* 3600	1400	4 310 000	*c* 3778	1652	4 550 000	*c* 4378
Granite:															
317	183	9.0	147	667	4 410 000	2366	767	3 946 000	3019	1600	3 910 000	3359	.....	.....	4592
212	183	8.0	148	933	3 467 000	2586	966	3 800 000	3957	933	4 520 000	3469	2231	4 680 000	4731
175	183	8.5	148	.....	.....	2633	.....	.....	3982	.....	.....	5145	.....	.....	*d* 5913
175	181	8.2	148	950	4 290 000	*c* 3054	1350	4 420 000	*c* 3900+	1700	4 480 000	*c* 3900+	1962	4 770 000	*c* 5086
Gravel:															
23	181	7.75	146	867	2 893 000	1898	967	3 660 000	2467	1267	4 247 000	2804	.....	.....	3165
22	183	6.0	152	1800	3 675 000	*a* 3705	.....	.....	.....	.....	.....	.....	.....	.....	.....
37	183	8.75	145	.....	.....	2481	1250	5 000 000	*a* 2895	1750	4 930 000	*a* 3325	.....	.....	.....
35	183	6.0	150	933	5 007 000	2866	.....	.....	.....	1900	4 573 000	*e* 3628	.....	.....	.....
24	183	7.0	149	1400	3 470 000	*a* 3111	1000	4 230 000	*a* 3826	1450	5 230 000	*f* 4029	2300	5 180 000	*a g* 4726
39	183	.....	146	1930	5 213 000	4126	2300	5 747 000	4938	2667	5 473 000	5241	2700	5 720 000	5710
26	181	11.0	143	400	2 313 000	989	800	2 977 000	1733	1100	3 407 000	2250	.....	.....	2333
25	182	10.0	138	333	2 013 000	888	667	2 656 700	1467	767	3 120 000	1895	.....	.....	2108
36	183	6.5	153	1033	4 137 000	3347	.....	.....	.....	1667	5 093 000	*h* 4658	.....	.....	.....
501	181	9.4	145	1050	4 600 000	*c* 3175	2100	4 620 000	*i* 3821	1550	5 240 000	*c* [illegible]0+	2129	5 395 000	*c* 5245

Trap rock:															
506.......	(b)	....	146	....	....	....	....	....	....	....	....	....	866	2 900 000	1904
450.......	186	10. 2	142	565	2 530 000	1944	865	2 750 000	2109	....	....	....	....	....	....
Cinders: 507..	181	19. 0	119	450	1 610 000	1647	800	1 820 000	2217	900	2 120 000	2525	1575	2 114 000	2761

[a] Average of 2 tests.
[b] Natural screenings from the same coarse aggregate.
[c] Average of 21 tests.
[d] Ultimate stress at 78 weeks, 5330.
[e] At 78 weeks, yield point 1930; modulus, 4 813 000; ultimate stress, 5016.
[f] Exceeded capacity of testing machine.
[g] At 78 weeks, yield point 2350 and ultimate stress 4740 (average of 2 tests).
[h] At 78 weeks, yield point 3200; modulus, 5 226 000; ultimate stress, 5615.
[i] 17 of 21 tests exceeded the capacity of the machine.

TABLE 9

Yield Point, Modulus of Elasticity, and Compressive Strength of Portland Cement Concretes Made with 35 Different Aggregates

[All results are the average of 3 tests of 8 by 16 inch cylinders unless otherwise noted. All concrete was mixed in the proportion, by volume, of 1 part cement to 3 parts fine aggregate to 6 parts coarse aggregate]

Aggregates		Per cent mixing water for quaking consistency	Weight per cubic foot (pounds)	Age when tested, 4 weeks			Age when tested, 13 weeks			Age when tested, 26 weeks			Age when tested, 52 weeks		
Coarse, crusher run or bank run	Sand passing $\frac{1}{4}$-inch screen			Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)	Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)	Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)	Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)
Limestone:															
169	182	8.0	144	600	2 450 000	1450	...	...	...	...	...	...	...	...	...
388	184	8.0	151	...	...	1164	567	3 386 000	1769	...	...	...	...	...	...
388	185	8.0	148	...	...	980	333	2 600 000	1413	...	...	...	...	...	...
163	181	7.5	149	467	3 017 000	1425	733	3 240 000	2391	767	3 673 000	2717	...	...	3006
166	182	9.0	140	400	1 437 000	1056	567	2 653 000	1584	533	3 053 000	1617	...	...	1856
128	183	7.5	150	800	4 425 000	b 2543	750	5 250 000	b 2946	700	3 000 000	b 1980	...	...	b 3064
251	183	8.0	152	633	3 383 000	2351	667	4 133 000	2613	933	4 520 000	2872	...	...	...
307	183	8.2	146	...	...	1557	...	...	1971	...	...	2274	...	...	3028
307	(a)	10.3	146	...	...	b 769	...	...	b 1057	...	...	b 1144	...	...	...
160	181	8.0	151	767	4 496 000	3023	1133	4 603 000	3079	1000	5 286 000	3847	...	...	3915
136	183	7.0	150	900	3 710 000	b 2157	1050	5 150 000	b 2835	1200	4 830 000	b 3136	...	...	b 3250
133	183	7.3	151	1350	2 340 000	b 2338	1150	3 295 000	b 2926	1050	4 633 000	b 3138	...	...	b 3190
150	181	7.5	152	533	3 860 000	1851	833	3 560 000	2792	1266	4 046 000	3184	...	...	3697
148	181	7.0	148	500	2 686 000	1978	833	3 646 000	2355	833	4 100 000	2833	...	...	3112
147	181	7.0	148	467	2 016 000	1839	900	2 193 000	2330	600	3 763 000	2584	1333	3 920 000	3168
145	181	7.0	150	1230	2 537 000	2767	1100	3 156 000	3317	1300	4 546 000	3966	...	...	3988
139	183	7.0	152	1200	3 955 000	b 2512	850	5 850 000	b 3105	1100	4 670 000	b 3626	...	...	4104
152	181	7.5	149	667	3 270 000	1689	900	3 950 000	2539	867	4 520 000	2748	...	...	3209
172	183	7.5	150	567	3 243 000	1553	900	3 410 000	1984	...	...	...	...	...	...
210	183	8.8	143	500	2 927 000	1154	733	3 460 000	1770	1350	3 270 000	b 2290	1460	3 927 000	c 2538

Granite:															
212	183	8.5	146	370	2 453 000	988	366	3 087 000	[b]1672	467	4 613 000	1896	334	4 460 000	2208
175	183	9.0	148	....	....	1327	....	....	2473	....	....	2578	....	....	3086
317	181	8.3	142	....	....	1111	....	....	1615	....	....	1768	....	....	2403
Gravel:															
23	181	8.0	142	....	3 210 000	773	500	2 527 000	1274	600	3 330 000	1465	....	....	1645
22	183	6.0	151	1350	3 740 000	[b]2606	....	....	....	....	....	....	....	....	....
37	183	9.0	144	....	....	1304	600	3 160 000	[b]1737	900	4 340 000	[b]2009	....	....	....
35	183	7.0	149	567	3 587 000	1548	900	3 900 000	[b]2043	....	....	2206	....	....	....
35	(a)	6.0	151	900	3 767 000	2134	800	4 703 000	2420	....	....	2641	....	....	....
24	183	6.25	151	1000	3 200 000	[b]2175	1050	5 010 000	[b]2993	850	4 500 000	[b]3074	....	....	....
39	183	8.5	144	....	....	1678	....	....	2260	....	....	2570	....	....	2978
26	181	10.0	141	200	1 527 000	534	367	2 343 000	993	500	2 800 000	1302	....	....	1494
36	183	6.6	148	600	2 900 000	1568	767	5 060 000	2039	1130	4 467 000	2458	....	....	....
35	(a)	6.8	153	867	3 600 000	2235	867	4 580 000	2775	1166	4 880 000	3163	....	....	....
25	182	9.0	139	300	1 513 000	622	367	2 353 000	1002	533	2 636 700	1358	....	....	1374
Trap rock, 450	186	9.7	139	340	3 120 000	1172	668	2 600 000	1487	....	....	....	....	....	....

[a] Natural screenings from the same coarse aggregate. [b] Average of 2 tests. [c] At 78 weeks, 3004 (1 test only).

TABLE 10

Yield Point, Modulus of Elasticity, and Compressive Strength of Portland Cement Concretes Made With 13 Different Aggregates

[All concrete was mixed in the proportion by volume of 1 part cement to 1 part fine aggregate to 5 parts coarse aggregate. All results are the average of 3 tests of 8 by 16 inch cylinders unless otherwise noted.]

Aggregates		Per cent for quaking consistency	Weight per cubic foot (pounds)	Age when tested, 4 weeks			Age when tested, 13 weeks			Age when tested, 26 weeks		
Coarse, crusher run or bank run	Sand passing $\frac{1}{4}$-inch screen			Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)	Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)	Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)
Limestone:												
251	183	7.4	148	367	863 000	[b] 2288	750	3 070 000	[b] 2615	...	...	...
251	(a)	9.3	152	800	2 320 000	[b] 2464	...	...	...	...	...	...
307	183	11.5	148	...	...	2332	...	...	3468	...	...	[c] 3058
307	(a)	9.7	148	...	...	[b] 1266	...	...	[b] 1476	...	...	[b] 1932
Granite:												
212	183	8.3	154	234	3 306 000	1555	...	...	...	...	...	...
317	183	8.4	149	...	...	1914	...	...	2175	...	...	[d] 2600
Gravel:												
37	183	9.2	134	567	3 087 000	1546	...	...	2180	...	...	2425
35	183	5.5	152	1100	4 986 000	3666	...	...	...	2100	5 207 000	[e] 4008
35	(a)	5.7	154	833	4 573 000	2646	...	...	...	...	...	...
36	(a)	5.4	155	1400	3 847 000	3315	...	...	...	...	...	...
28a	(a)	8.0	145	400	3 120 000	1296	850	3 660 000	[b] 2024	...	...	[b] 2105
Trap rock: 450	186	7.7	131	590	2 870 000	1310	...	...	...	...	...	...

[a] Natural screenings from the same coarse aggregate.

[b] Average of 2 tests.

[c] 52 weeks, 3880 (average of 2 tests).

[d] 52 weeks, 3477.

[e] 78 weeks, yield point, 3167; modulus, 4 633 000; ultimate stress, 5468.

TABLE 11

Yield Point, Modulus of Elasticity, and Compressive Strength of Portland Cement Concretes Made With 11 Different Aggregates

[All concrete was mixed in the proportion by volume of 1 part cement to 2 parts of fine aggregate to 7 parts of coarse aggregate. All results are the average of 3 tests of 8 by 16 inch cylinders unless otherwise noted]

Aggregates		Per cent mixing water for quaking consistency	Weight per cubic foot (pounds)	Age when tested, 4 weeks			Age when tested, 13 weeks			Age when tested, 26 weeks		
Coarse, crusher run or bank run	Sand passing $\frac{1}{4}$-inch screen			Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)	Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)	Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)
Limestone:												
166	183	14.0	140	450	1 850 000	[b] 1381	600	2 695 000	[b] 1586	...	...	...
251	183	6.4	145	300	2 085 000	[b] 1375	400	2 620 000	[b] 1645	700	3 150 000	[b] 2082
251	(a)	9.4	152	350	2 170 000	[b] 1279	...	...	...	...	...	...
147	183	8.0	151	650	2 110 000	[b] 2365	600	4 435 000	[b] 2193	1200	3 950 000	[c] 2360
Granite: 212	183	4.5	153	234	2 753 000	993	...	...	...	...	...	...
Gravel:												
37	183	8.3	145	...	...	1525	...	...	1617	600	4 840 000	[b] 2243
35	183	5.5	151	766	4 130 000	1972	700	4 090 000	2081	...	...	2658
24	183	5.8	153	1000	2 720 000	[b] 2231	1050	4 750 000	[b] 3122	1050	5 240 000	[d] 3494
36	183	5.7	152	867	3 080 000	2443	800	4 190 000	2856	1060	4 566 000	3051
28a	(a)	7.3	149	450	3 080 000	[b] 1614	800	3 370 000	[b] 2184	...	...	[b] 2346
Trap rock: 450	186	9.4	136	395	2 060 000	1199	...	...	...	...	...	...

[a] Natural screenings from the same coarse aggregate were used.
[b] Average of 2 tests.
[c] At 52 weeks, yield point, 1750; modulus, 4 440 000; ultimate stress, 3882 (average of 2 tests).
[d] At 52 weeks, yield point, 1750; modulus, 4 520 000; ultimate stress, 3289 (average of 2 tests).

TABLE 12

Yield Point, Modulus of Elasticity, and Compressive Strength of Portland-Cement Concretes, Proportioned by the Void Method, Using a Large Number of Different Aggregates

[All results the average of 3 tests of 8 by 16 inch cylinders unless otherwise noted]

Aggregates		Proportions by volume (cement: sand: stone)	Per cent mixing water for quaking consistency	Weight per cubic foot (pounds)	Age when tested, 4 weeks			Age when tested, 13 weeks			Age when tested, 26 weeks			Age when tested, 52 weeks		
Coarse, crusher run or bank run	Sand passing ¼-inch screen				Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)	Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)	Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)	Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)
Limestone:																
169	183	1:2.4:5.8	7.4	146	600	2 880 000	a 2087	850	3 615 000	a 2473	1100	2 735 000	a 2708	......	......	a 2834
81	180	1:2.22:6.51	6.6	......	......	3 000 000	1458	......	5 430 000	1735	......	4 610 000	2147	......	4 240 000	2109
31	180	1:2.22:5.70	6.8	......	......	4 870 000	1903	......	3 970 000	2100	......	5 900 000	2632	......	......	2582
163	183	1:2.4:5.85	7.0	151	1150	3 485 000	a 2753	850	4 515 000	a 3629	1000	4 750 000	a 3362	......	......	a 3994
166	183	1:2.4:6.45	14.0	139	400	1 725 000	a 1115	450	2 535 000	a 1369	550	2 810 000	a 1445	......	......	a 1648
123	183	1:2.16:4.5	7.0	154	......	......	......	......	......	......	833	4 880 000	3076	......	......	c 3043
30	180	1:2.2:5.25	6.7	147	......	3 180 000	2373	......	3 850 000	2796	......	4 400 000	2888	......	4 200 000	3601
251	183	1:2.4:4.47	8.6	152	733	3 207 000	2591	1300	4 043 000	3299	1133	4 207 000	4105	1700	4 673 000	4228
307	183	1:2.4:4.25	7.4	148	......	......	2135	......	......	2614	......	......	3098	......	......	3900
160	183	1:2.4:5.46	7.0	151	900	4 425 000	a 3142	1700	5 040 000	a 3956	1400	5 840 000	a 4140	......	......	a, b 3531
136	131	1:2.6:6.68	8.5	151	633	3 247 000	2233	867	4 273 000	2652	1073	4 253 000	2904	......	......	3463
133	183	1:2.4:5.6	6.2	153	700	2 115 000	a 2075	......	......	a 2318	......	......	......	......	......	......
150	183	1:2.4:5.81	8.2	151	600	3 135 000	a 2315	1000	4 315 000	a 3116	1400	4 050 000	a 3222	......	......	a 2463
148	183	1:2.4:6.37	8.2	149	700	2 825 000	a 2042	700	4 125 000	a 3019	950	4 140 000	a 2910	......	......	a 3167
147	183	1:2.4:5.97	9.0	149	750	2 010 000	a 2126	600	3 780 000	a 2926	850	4 970 000	a 3219	1250	4 000 000	a 3363
145	183	1:2.4:5.57	7.5	150	1550	2 750 000	a 3437	1050	4 700 000	c, d 3889+	1560	6 020 000	c, d 3979+	......	......	a, e 4580
139	183	1:2.4:5.38	7.0	153	800	4 780 000	a 3447	2300	5 230 000	c, d 3979+	......	......	......	......	......	a, f 5718
152	183	1:2.4:5.81	8.0	151	1100	3 625 000	a 2588	700	4 880 000	a 3719	1500	4 770 000	a 3775	......	......	a 3871
172	183	1:2.4:5.45	7.0	153	1000	3 600 000	a 2688	1400	3 330 000	3990	950	4 395 000	a 3849	......	......	a 3947
210	183	1:2.4:6.26	9.3	143	367	2 806 000	1074	434	3 867 000	1513	......	......	1732	......	......	......

Granite:																
212.....	183	1:2.4:4.92.	4.9	149	500	4 000 000	*a* 1998	1250	2 360 000	*a* 3065	1200	3 960 000	*a* 3191	1200	4 480 000	*a* 3896
317.....	183	1:2.4:4.62.	8.3	143	....	....	1795	....	....	2296	....	....	2598	....	....	3880
Gravel:																
14......	180	1:2.22:7.03	6.8	....	....	5 720 000	925	....	3 320 000	1389	....	3 700 000	*a* 1510	....	3 820 000	1991
23......	183	1:2.4:8.34.	7.0	149	650	2 425 000	*a* 1368	750	3 975 000	*a* 1677	700	4 135 000	*a* 1792	....	....	*a* 2378
22......	181	1:2.4:8.00.	7.6	151	367	2 570 000	964	667	3 060 000	1369	833	3 873 000	1692	567	5 293 000	1629
35......	183	1:2.4:7.00.	5.4	151	833	4 333 000	2110	1167	4 338 000	2721	....	....	2612	....	....	....
24......	181	1:2.6:11.4.	5.0	153	467	2 718 000	1489	667	3 078 000	2195	767	4 993 000	2372	....	....	2869
39......	183	1:2.4:6.2..	7.5	146	1130	4 160 000	3880	1370	4 813 000	3350	1900	4 933 000	4013	....	....	*a* 4407
36......	183	1:2.3:6.4..	6.1	153	733	3 570 000	2641	1000	4 773 000	3262	1133	4 913 000	3483	....	....	....
26......	183	1:2.6:9.79.	9.0	145	400	2 375 000	*a* 932	450	3 430 000	1237	700	3 735 000	1415	....	....	*a* 1737
25......	183	1:2.4:7.7..	12.0	135	200	675 000	*a* 322	200	1 060 000	*a* 523	200	1 955 000	*a* 566	....	....	*a* 647
15......	180	1:2.23:10.2	6.6	....	....	1 280 000	*a* 287	....	1 910 000	*a* 586	....	1 975 000	622	....	2 040 000	736

a Average of 2 tests.
b At 78 weeks, ultimate stress, 4774 pounds per square inch.
c Average of 4 tests.
d Exceeded capacity of testing machine.
e Ultimate stress: At 78 weeks, 4689 (average of 4 tests); at 104 weeks, 6645 (average of 2 tests).
f At 78 weeks, ultimate stress, 6316 pounds per square inch.

TABLE 13

Comparison of the Compressive Strengths of Concretes Proportioned by the Void Method and Arbitrarily Proportioned Mixtures as Generally Assumed in Practice

[All results are the average of 3 or more tests. Fine aggregate sand 183]

Coarse aggregate	Proportions by volume (cement : sand : stone)	Compressive strength, pounds per square inch at the following ages:				
		4 weeks	13 weeks	26 weeks	52 weeks	78 weeks
Limestone:						
251	Theoretical (1 : 2.4 : 4.47)	2591	3299	4105	4228	
	1 : 3 : 6	2351	2613	2872		
	1 : 2 : 4	3370	3630	4601		
307	Theoretical (1 : 2.4 : 4.45)	2135	2614	3098	3900	
	1 : 3 : 6	1557	1971	2274	3028	
	1 : 2 : 4	2161	2851	3175	4247	
160	Theoretical (1 : 2.4 : 5.46)	3142	3956	4140	3531	
	1 : 3 : 6	3023	3079	3847	3915	
	1 : 2 : 4	2879	3962		4981	5505
136	Theoretical (1 : 2.6 : 6.68)	2233	2652	2904	3463	
	1 : 3 : 6	2157	2835	3136	3250	
	1 : 2 : 4	3984		3999	5975	7285
150	Theoretical (1 : 2.4 : 5.81)	2315	3116	3222	2463	
	1 : 3 : 6	1851	2792	3184	3697	
	1 : 2 : 4	2596	3926	3904	4646	
Granite:						
212	Theoretical (1 : 2.4 : 4.92)	1998	3065	3191	3896	
	1 : 3 : 6	988	1672	1986	2208	
	1 : 2 : 4	2586	3957	3469	4731	

Gravel:						
35	Theoretical (1 : 2.4 : 7.00)	2110	2721	2612	...	...
	1 : 3 : 6	1548	2043	2306	...	...
	1 : 2 : 4	3347	...	4658	...	3615
39	Theoretical (1 : 2.4 : 6.20)	3380	3350	4013	4407	...
	1 : 3 : 6	1678	2260	2570	4407	...
	1 : 2 : 4	4126	4938	5246	5710	...
36	Theoretical (1 : 2.3 : 6.40)	2641	3262	3482	...	...
	1 : 3 : 6	1568	2089	2458	...	...
	1 : 2 : 4	3347	...	4658	...	5615

TABLE 14

Yield Point, Modulus of Elasticity, and Compressive Strength of Portland Cement Concretes Made of a Number of Different Aggregates of Odd Proportions of Cement to Fine and Coarse Aggregate

[All results are the average of 3 tests of 8 by 16 inch cylinders unless otherwise noted]

Aggregate		Proportions by volume (cement: sand: stone)	Per cent mixing water for quaking consistency	Weight per cubic foot (pounds)	Age when tested, 4 weeks			Age when tested, 13 weeks			Age when tested, 26 weeks		
Coarse, crusher run or bank run	Sand passing ¼-inch screen				Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)	Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)	Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)
Limestone:													
388	184	1:0.5:5.5	8.0	153	....	....	1434	....	....	1826	....	....	....
388	185	1:0.5:5.5	8.0	143	....	....	1003	433	2 440 000	1331	....	....	....
383	184	1:1:8	....	149	....	....	1102	....	....	1342	....	....	....
388	185	1:1:8	....	147	....	....	769	167	3 253 000	1178	....	....	....
307	183	1:2.5:6.5	9.1	150	....	....	1248	....	....	1598	....	....	c 2009
210	183	1:0:6	11.0	144	400	2 573 000	1239	600	3 400 000	1724	750	2 293 000	b, d 1803
Granite:													
212	183	1:0:9	10.7	144	800	2 207 000	890	900	3 260 000	1182	500	2 940 000	e 1322
317	183	1:2.5:6.5	9.6	147	....	....	1389	....	....	1535	....	....	f 2009
Gravel:													
35	(a)	1:1.5:7.5	5.6	149	400	3 660 000	b 1059	....	....	....	....	....	....
36	(a)	1:2.5:6.5	6.6	153	800	2 833 000	1684	....	....	....	....	....	....
36	183	1:1.5:4.5	6.3	153	1200	4 077 000	3559	....	....	....	1200	5 587 000	g 4192
28	None.	1:0:6	9.2	141	400	1 913 000	b 1120	600	1 973 000	b 1539	....	....	b 1911
28	None.	1:0:9	9.5	141	....	....	b 527	....	....	b 769	....	....	b 963
Trap rock:													
450	186	1:3:3	12.1	136	420	2 230 000	1411	....	....	....	....	....	....
450	186	1:4:5	11.1	135	268	1 520 000	926	....	....	....	....	....	....

[a] Natural screenings from same material used.
[b] Average of 2 tests.
[c] At 52 weeks, ultimate stress, 2558.
[d] At 52 weeks, ultimate stress, 2568 (average of 4 tests).
[e] At 52 weeks, ultimate stress, 2104 (average of 2 tests).
[f] At 52 weeks, ultimate stress, 2627.
[g] At 78 weeks, yield point, 2130; modulus, 5 213 000; ultimate stress, 5639.

TABLE 15

Compressive Strength of Portland Cement Concretes at the Age of Four Weeks, Prepared with 60 Different Aggregates in Various Proportions, by Volume (Cement, Sand, Stone, or Gravel) Mixed to a Quaking Consistency

[All results are the average of 3 tests of 6-inch cubes unless otherwise noted]

Aggregate		1:0:6			1:1:5			1:2:4			1:3:3			1:0:9		
Coarse, crusher run or bank run	Sand passing ¼-inch screen	Per cent water	Weight per cubic foot (pounds)	Ultimate stress (lbs. per sq. in.)	Per cent water	Weight per cubic foot (pounds)	Ultimate stress (lbs. per sq. in.)	Per cent water	Weight per cubic foot (pounds)	Ultimate stress (lbs. per sq. in.)	Per cent water	Weight per cubic foot (pounds)	Ultimate stress (lbs. per sq. in.)	Per cent water	Weight per cubic foot (pounds)	Ultimate stress (lbs. per sq. in.)
Granite:																
212	183	8.25	134	1339	7.3	152	2955	8.8	150	2382	10.3	144	1389	5.5	128	860
175	183	7.9	140	1442	9.9	148	1324	10.3	142	1023	11.4	139	787	8.5	137	854
175	181	....	....	....	....	....	....	8.2	146	a 3802	....	....	....	....	....	....
317	183	9.8	132	1055	9.0	149	1958	10.2	145	1730	11.0	143	1330	8.4	124	738
Cinder: 507	181	....	....	....	....	....	....	18.9	118	a 2154	....	....	....	....	....	....
Limestone:																
388	184	8.5	153	2503	9.3	155	2530	9.9	154	2018	10.3	147	1311	7.8	134	944
388	185	....	....	....	9.6	150	1987	10.8	146	1622	12.7	140	1057	....	....	....
251	183	8.0	132	690	8.2	152	2469	8.3	152	2555	11.8	144	1728	6.4	121	722
251	(b)	8.1	128	1124	10.8	150	1766	12.3	148	1510	13.6	144	1016	6.8	125	749
307	183	9.2	128	921	8.6	151	1785	8.9	149	2243	10.1	142	1360	....	....	....
307	(b)	....	....	....	10.1	146	1398	10.6	149	1450	11.0	149	1558	8.3	124	477
160	181	....	....	....	....	....	....	9.3	149	3375	....	....	....	3.4	128	923
150	183	....	....	....	....	....	....	9.0	147	3184	....	....	....	8.4	136	1203
147	183	....	....	....	....	....	....	9.4	147	2690	....	....	....	8.6	139	1371
210	183	9.5	148	2060	10.4	146	1718	10.2	144	1638	11.0	140	1062	9.3	146	1294
500	181	....	....	....	....	....	....	10.0	145	a 3392	....	....	....	....	....	....

[a] Average of 21 tests.

[b] Natural screenings from same material used.

TABLE 15—Continued

Compressive Strength of Portland Cement Concretes at the Age of Four Weeks, Prepared with 60 Different Aggregates in Various Proportions, by Volume (Cement, Sand, Stone, or Gravel) Mixed to a Quaking Consistency—Continued

Aggregate		1:0:6			1:1:5			1:2:4			1:3:3			1:0:9		
Coarse, crusher run or bank run	Sand passing ¼-inch screen	Per cent water	Weight per cubic foot (pounds)	Ultimate stress (lbs. per sq. in.)	Per cent water	Weight per cubic foot (pounds)	Ultimate ctress (lbs. per sq. in.)	Per cent water	Weight per cubic foot (pounds)	Ultimate stress (lbs. per sq. in.)	Per cent water	Weight per cubic foot (pounds)	Ultimate stress (lbs. per sq. in.)	Per cent water	Weight per cubic foot (pounds)	Ultimate stress (lbs. per sq. in.)
Gravels:																
37	183	....	125	1018	....	145	1918	....	144	1570	....	141	1092	....	....	....
37	(a)	....	....	....	10.1	143	1585	10.9	141	1440	11.1	142	1435	10.1	118	437
35	183	5.3	140	1408	6.3	155	3035	6.7	150	3175	8.0	144	2011	3.8	124	774
35	(a)	....	....	....	6.0	154	3634	6.7	151	3104	8.3	146	1902	....	....	....
24	183	....	....	....	....	....	....	7.0	152	3520	....	....	....	4.8	135	1063
39	183	7.0	136	1408	8.5	148	2175	8.8	145	1572	10.0	142	982	....	....	....
39 b	183	7.6	120	1226	7.7	138	1788	8.5	146	1704	11.1	143	1429	....	....	....
36	183	5.8	140	1487	6.4	152	3456	7.6	151	2974	8.5	147	2206	4.5	136	869
36	(a)	....	....	....	7.0	155	2693	6.8	153	3376	....	....	....	....	....	....
28	183	10.5	144	1014	....	....	....	12.5	140	927	....	....	....	10.4	138	613
28a	183	10.4	132	1120	8.2	152	1560	9.2	150	1383	10.9	147	955	5.2	127	934
28a	(a)	....	....	....	8.0	148	1635	9.0	150	1434	9.5	147	127	....	....	....
501	181	....	....	....	....	....	....	9.3	142	c 3997	....	....	....	....	....	....

Aggregate		1:1:8			1:2:7			1:3:6			1:4:5			Theoretical [d]		
Coarse, crusher run or bank run	Sand passing ¼-inch screen	Per cent water	Weight per cubic foot (pounds)	Ultimate stress (lbs. per sq. in.)	Per cent water	Weight per cubic foot (pounds)	Ultimate stress (lbs. per sq. in.)	Per cent water	Weight per cubic foot (pounds)	Ultimate stress (lbs. per sq. in.)	Per cent water	Weight per cubic foot (pounds)	Ultimate stress (lbs. per sq. in.)	Per cent water	Weight per cubic foot (pounds)	Ultimate stress (lbs. per sq. in.)
Granite:																
212	183	6.5	140	1313	7.6	152	1410	8.5	147	1147	...	...	...	4.9	149	2402
175	183	8.8	146	1052	8.3	147	1032	9.9	144	761	...	...	...	...	...	...
175	183	...	...	...	...	...	...	9.0	151	1544	...	...	...	...	...	...
317	183	8.3	135	1169	9.6	147	1393	10.5	143	993	11.0	139	812	...	...	...
317	183	...	...	...	...	...	...	10.6	147	1402	...	...	...	...	...	...
Limestone:																
169	182	...	...	...	...	...	...	8.0	144	2012	...	...	...	...	...	...
81	180	...	...	...	...	...	...	...	...	...	...	...	...	6.6	...	2006
31	180	...	...	...	...	...	...	...	...	...	...	...	...	6.8	...	2784
388	184	8.2	149	1726	8.5	152	1471	9.1	151	1195	9.7	148	852	...	...	...
388	185	8.8	152	1994	9.5	151	1590	11.2	145	1053	11.8	140	685	...	...	...
163	181	...	...	...	...	...	...	7.5	149	2156	...	...	...	...	...	...
166	182	...	...	...	...	...	...	9.0	...	1391	...	...	...	...	...	...
30	180	...	...	...	...	...	...	...	...	...	...	...	...	6.7	...	3590
251	183	7.0	134	1029	8.1	147	1538	9.4	150	1466	9.6	142	1112	...	...	...
251	(a)	8.6	132	903	10.0	150	1192	11.0	150	942	...	...	...	...	...	...
307	183	7.3	137	1105	7.9	150	1563	9.6	147	1057	9.9	145	818	...	...	...
307	(a)	8.9	138	835	9.3	149	1220	9.2	148	1465	11.0	149	1050	...	...	...
160	181	7.7	143	1459	7.5	150	2450	8.7	147	1726	8.5	147	1648	...	...	...
136	181	...	...	...	...	...	...	...	...	...	...	...	...	8.5	151	2793
133	183	...	...	...	...	...	...	7.3	150	2558	...	...	...	6.2	155	2497
150	183	6.6	137	1056	10.0	147	1763	9.0	148	1301	10.3	146	1147	...	...	...
150	183	...	...	...	...	...	...	7.5	153	2254	...	...	...	...	...	...
148	181	...	...	...	...	...	...	...	...	...	...	...	...	7.0	150	1960

[a] Natural screenings from same material used. [b] Fine material passing ¼-inch screen removed for this test. [c] Average of 21 tests. [d] See text, p. 39.

TABLE 15—Continued

Compressive Strength of Portland Cement Concretes at the Age of Four Weeks, Prepared with 60 Different Aggregates in Various Proportions. by Volume (Cement, Sand, Stone, or Gravel) Mixed to a Quaking Consistency—Continued

Aggregate		1:1:8			1:2:7			1:3:6			1:4:5			Theoretical		
Coarse, crusher run or bank run	Sand passing ¼-inch screen	Per cent water	Weight per cubic foot (pounds)	Ultimate stress (lbs. per sq. in.)	Per cent water	Weight per cubic foot (pounds)	Ultimate stress (lbs. per sq. in.)	Per cent water	Weight per cubic foot (pounds)	Ultimate stress (lbs. per sq. in.)	Per cent water	Weight per cubic foot (pounds)	Ultimate stress (lbs. per sq. in.)	Per cent water	Weight per cubic foot (pounds)	Ultimate stress (lbs. per sq. in.)
Limestone—Continued																
147	183	9.9	147	1880	8.2	147	2025	9.1	148	2553						
147	183							7.0	150	2306						
147	(a)							9.5	145	1501						
145	181							7.0	148	3186						
139	183							7.0	153	3230						
152	181							7.5	150	1507						
210	183	8.8	148	1152	9.0	147	1216	10.0	146	881						
210	183							8.8	148	1350						
Gravels:																
14	180													6.8		1483
23	181							8.0		1086						
22	181													7.6		1358
37	183	10.5	124	644	10.1	143	1232	10.3	143	1029	12.0	142	1020			
37	(a)	8.7	126	1046	9.0	142	1164	9.7	144	1237	10.2	142	1088			
35	183	7.5	136	1353	5.5	153	2491	6.0	152	2053	7.5	144	1237	5.4	150	2058
35	(a)	4.5	143	1226	5.5	151	2247	6.2	151	1940	8.2	143	809			
24	183	5.7	146	1560	5.8	152	2945	6.3	151	1925	7.3	144	1780		155	2462
39	183	7.6	135	1439				9.6	143	1917						
26	181							10.0	142	660						
36	183	5.3	149	1085	5.7	153	2556	16.9	149	2240	7.8	147	1590			
36	(a)	5.2	142	799	6.8	151	2031	6.7	154	2180						

25	182							9.0	140	718						
28	183							12.3	138	425						
28a	183	7.2	141	1338	7.7	152	1798	9.5	149	1300	10.3	145	1020			
28a	(a)	6.8	136	1090	7.4	150	1664	8.3	149	1345	9.1	146	934			
15	180													6.6		670

Aggregate		1:0.5:5.5			1:1½:4½			1:4:2			1:1½:7½			1:2½:6½		
Coarse, crusher run or bank run	Sand passing ¼-inch screen	Per cent water	Weight per cubic foot (pounds)	Ultimate stress (lbs. per sq. in.)	Per cent water	Weight per cubic foot (pounds)	Ultimate stress (lbs. per sq. in.)	Per cent water	Weight per cubic foot (pounds)	Ultimate stress (lbs. per sq. in.)	Per cent water	Weight per cubic foot (pounds)	Ultimate stress (lbs. per sq. in.)	Per cent water	Weight per cubic foot (pounds)	Ultimate stress (lbs. per sq. in.)
Granite: 175	183										8.0	140	1256			
Limestone:																
251	183							12.4	136	1113						
251	(a)										9.1	152	1663	10.8	150	1044
388	184	8.5	154	2275	9.1	153	1901				7.9	153	1832			
388	185	8.5	153	2248										8.8	150	1603
307a	183				9.1	151	1856									
317	183										8.9	144	1315	9.1	148	1504
Gravel:																
35	183	5.3	147	1780	6.3	152	3015	10.0	140	1309	5.1	147	1697	6.0	150	1736
35	(a)	5.7	145	1342	6.8	153	2755	9.5	139	1119	5.4	150	2663	6.6	150	1873
36	183	5.8	152	2543	6.7	155	4101	10.2	140	1500	5.0	143	2325	6.7	151	2376
36	(a)	6.3	145	2116	6.5	153	3345				5.8	152	1902	6.4	151	2260
28a	(a)													7.6	150	1454

[a] Natural screenings from same material used.

TABLE 16

Compressive Strength of Portland Cement Concretes at Various Ages Prepared With a Number of Aggregates in 3 Different Proportions by Volume (Cement, Sand, Stone, or Gravel) Mixed to a Quaking Consistency

[All results are the average of 3 tests of 6-inch cubes unless otherwise noted]

Aggregates		Theoretical [a]							1 : 3 : 6						1 : 2 : 4					
Coarse, crusher run or bank run	Sand passing ¼-inch screen	Actual proportions	Per cent water	Wt. per cubic foot (lbs.)	Ultimate stress (lbs. per sq. in.) and age (in weeks)				Per cent water	Wt. per cubic foot (lbs.)	Ultimate stress (lbs. per sq. in.) and age (in weeks)				Per cent water	Wt. per cubic foot (lbs.)	Ultimate stress (lbs. per sq. in.) and age (in weeks)			
					4	13	26	52			4	13	26	52			4	13	26	52
Limestone:																				
81	180	1 : 2.22 : 6.51	6.6		2006	2560	2437	3103												
31	180	1 : 2.22 : 5.70	6.8		2784	3013	3700	3823												
163	181								7.5	150	2156	3075	3427	3743						
166	182								9.0	141	1391	2080	2295	2318						
30	180	1 : 2.2 : 5.25	6.7	146	3590	3999	3877	4843												
136	181	1 : 2.6 : 6.68	8.5	153	2793		3800	4254												
133	183	1 : 2.4 : 5.6	6.2	155	2497		3389	4130												
148	181								7.0	151	1960	2892	3310							
147	183								9.1	148	2553									
									7.0	149	2306	2563	3625	3747						
145	181								7.0	149	3186	3409	4758	4510						
139	183								7.0	153	3230	3545	4145	4015						
152	181								7.5	150	1507	2666	3470							
210	183								10.0	146	881									
	183								8.8	145	1350	2495	2465	2920						
500	181														10.0	146	b 3392	b 4421	b 4503	b 4942
Gravel:																				
23	181								8.0	141	1086	1509	1926	1877						
22	181	1 : 2.4 : 8.0	7.6	152	1358		2210	2290												
24	183	1 : 2.6 : 11.4	5.0	156	2462	2791	4130	3985												

39	183								9.6	142	1917	2740	2685							
26	181								10.0	143	660	1182	1614							
25	182								9.0	142	718	1176	1452	1726						
15	180	1 : 2.23 : 10.2	6.6		670	796	786	862												
14	180	1 : 2.23 : 7.03	6.8		1483	2139	1775	2630												
501	181														9.4	144	b 3997	b 4729	b 4830	b 5650
Granite:																				
212	183	1 : 2.4 : 4.92	4.9	149	2402	4235	4230	3535												
175	183								9.9	144	761									
									9.0	151	1544	1804	3191	3086						
175	181														8.2	147	3802	5040	5329	5964
Cinders:																				
507	181														19.0	118	2154	2571	2702	3117

[a] See text, p. 39.

[b] Average of 21 tests.

TABLE 17

Relative Compressive Strength of Portland Cement Concrete as Tested in 8 by 16 Inch Cylinders and 6-Inch Cubes; Concrete Mixed in the Proportion by Volume of 1 Part Cement to 2 Parts Sand 181 to 4 Parts Coarse Aggregate

[All results are the average of 21 tests]

Coarse aggregate	Per cent water used for quaking consistency	Ultimate stress (lbs. per sq. in.) at the following ages:							
		4 weeks		13 weeks		26 weeks		52 weeks	
		Cylinders	Cubes	Cylinders	Cubes	Cylinders	Cubes	Cylinders	Cubes
Granite 175	8.2	3054	3802	a 3900+	5040	a 3900+	b 5329+	5086	5964
Limestone 500	10.0	2492	3392	c 3600	4421	b 3778	4503	4378	4942
Gravel 501	9.3	3175	3997	d 3821	4729	a 3900+	c 4830	5245	5650
Cinders 507	18.9	1647	2154	2217	2571	2525	2702	2761	3117

[a] All test pieces exceeded the capacity of the testing machine.

[b] 3 test pieces exceeded the capacity of the testing machine.

[c] 1 test piece exceeded the capacity of the testing machine.

[d] 17 test pieces exceeded the capacity of the testing machine.

TABLE 18

Effect of Thoroughness of Mixing on the Compressive Strength of Concrete 8 by 16 Inch Cylinders

[Cement, sand, and coarse aggregate weighed by laboratory force. Mixing, including the addition of water by different contractors as designated. All test pieces molded by laboratory men]

Proportions by volume, 1 part cement to—	Method of mixing	Method of curing [a]	Age in weeks when tested	Concrete mixed by company A						Concrete mixed by company B					
				Per cent water [b]	Weight per cubic foot (lbs.)	Modulus of elasticity	Yield point (per cent ultimate strength)	Ultimate stress (lbs. per sq. in.)		Per cent water [b]	Weight per cubic foot (lbs.)	Modulus of elasticity	Yield point (per cent ultimate strength)	Ultimate stress (lbs. per sq. in.)	
								Range of 3 tests	Average					Range of 3 tests	Average
3 sand 183 : 6 gravel 39	Hand	Outside.	4	10.9	141	2 530 000	50	193	864	11.8	139	1 330 000	38	61	441
	...do	...do	13	11.0	140	1 480 000	63	227	852	12.0	143	1 120 000	40	29	577
	...do	Inside	4	11.7	144	1 880 000	43	185	622	11.0	142	2 300 000	39	134	590
	...do	...do	13	11.2	142	1 980 000	51	469	748	10.8	142	3 360 000	41	814	1313
	Machine	...do	4	10.7	143	2 770 000	43	346	840	13.8	145	2 110 000	42	81	558
	...do	...do	13	9.9	144	3 610 000	37	283	1358	13.8	146	2 670 000	43	134	937
	...do	Outside.	4	......	......	......	......	......	......	......	......	......	......	......	......
	...do	...do	13	......	......	......	......	......	......	......	......	......	......	......	......
3 sand 183 : 6 limestone 221	Hand	...do	4	12.3	138	1 180 000	40	47	419	14.5	139	1 010 000	38	41	390
	...do	...do	13	12.3	143	1 720 000	36	142	742	12.8	144	1 220 000	42	56	556
	Machine	...do	4	......	......	......	......	......	......	......	......	......	......	......	......
	...do	...do	13	......	......	......	......	......	......	......	......	......	......	......	......
2 sand 183 : 4 gravel 39	Machine	...do	4	11.0	141	2 910 000	37	120	1265	9.4	142	3 070 000	37	280	1630
	...do	...do	13	10.3	142	2 810 000	42	159	1740	9.4	142	3 700 000	32	90	2157
	...do	Inside	4	10.3	144	3 120 000	39	490	1443	9.4	144	3 600 000	41	233	1887
	...do	...do	13	10.3	143	3 920 000	42	......	c 1890	9.4	144	4 130 000	54	313	2485

Proportions by volume, 1 part cement to—	Method of mixing	Method of curing [a]	Age in weeks when tested	Concrete mixed by company C						Concrete mixed by laboratory force					
				Per cent water [b]	Weight per cubic foot (lbs.)	Modulus of elasticity	Yield point (per cent ultimate strength)	Ultimate stress (lbs. per sq. in.) Range of 3 tests	Ultimate stress (lbs. per sq. in.) Average	Per cent water [b]	Weight per cubic foot (lbs.)	Modulus of elasticity	Yield point (per cent ultimate strength)	Ultimate stress (lbs. per sq. in.) Range of 3 tests	Ultimate stress (lbs. per sq. in.) Average
3 sand 183 : 6 gravel 39	Hand	Outside	4	11.5	139	1 780 000	39	104	579	......	......	......	......	......	......
	do	do	13	11.9	142	1 410 000	53	100	694	......	......	......	......	......	......
	do	Inside	4	9.4	140	2 090 000	44	166	384	......	......	......	......	......	......
	do	do	13	11.0	142	2 660 000	48	132	827	......	......	......	......	......	......
	Machine	do	4	11.0	144	2 140 000	44	103	675	9.7	145	3 270 000	49	112	1027
	do	do	13	10.3	143	3 440 000	41	283	1130	9.8	144	3 430 000	48	108	1606
	do	Outside	4	......	......	......	......	......	......	9.8	140	2 380 000	38	135	709
	do	do	13	......	......	......	......	......	......	10.9	143	1 840 000	46	338	1092
3 sand 183 : 6 limestone 221	Hand	do	4	12.5	140	1 460 000	35	487	688	......	......	......	......	......	......
	do	do	13	12.1	145	1 820 000	50	794	861	......	......	......	......	......	......
	Machine	do	4	......	......	......	......	......	......	11.2	142	1 730 000	39	28	951
	do	do	13	......	......	......	......	......	......	11.2	142	2 190 000	41	90	1222
2 sand 183 : 4 gravel 39	do	do	4	9.4	142	4 990 000	28	384	2216	8.8	143	4 230 000	35	49	2572
	do	do	13	9.4	142	3 260 000	41	232	2132	8.9	144	3 870 000	42	64	2672
	do	Inside	4	9.4	143	4 200 000	29	351	1828	8.9	145	4 060 000	40	398	2312
	do	do	13	9.4	143	4 110 000	35	169	2308	8.9	145	4 310 000	42	164	2809

[a] "Outside"=stored in damp room 48 hours, then stored out of doors exposed to the weather; "inside"=stored in damp room until tested.
[b] Consistency varied from quaking to very fluid, depending upon amount of water used and thoroughness of mixing.
[c] One test only.

TABLE 19

Effect of the Method of Molding on the Compressive Strength of Portland Cement Concrete

[All results are the average of 3 tests of 8 by 16 inch cylinders. Consistency quaking]

Proportions by volume, 1 part cement to—	Method of molding and storage	Age when tested, 4 weeks				Age when tested, 13 weeks			
		Weight per cubic foot (pounds)	Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)	Weight per cubic foot (pounds)	Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)
6 gravel 503	In damp closet entire period	144	533	2 287 000	1898	144	500	2 457 000	1968
	In damp closet 4 weeks, then in fresh water.	148	633	2 575 000	1646	148	500	2 690 000	1825
2 sand 187 : 4 trap rock 505	Deposited through 5-inch tremie	153			1821	154			2156
	Immersed about 3 feet below surface of water after depositing in molds.	159			2851	159			3570+
	In damp room 24 hours before immersion.				3978+	157			3978+
	In damp room 8 weeks before immersion.					158			3190
2 sand 188 : 4 trap rock 505	do	157			2284	158			2557
3 sand 187 : 6 trap rock 505	Deposited through 5-inch tremie	157			459	158			760
	In damp room 8 weeks before immersion.					158			1948
3 sand 187 : 6 gravel 502	do					147			1816
5 sand 187 : 8 rock 505	do					157			1333

Proportions by volume, 1 part cement to—	Method of molding and storage	Age when tested, 26 weeks				Age when tested, 52 weeks			
		Weight per cubic foot (pounds)	Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)	Weight per cubic foot (pounds)	Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)
6 gravel 503	In damp closet entire period	146	766	2 428 000	2172	144	733	2 450 000	2400
	In damp closet 4 weeks, then in fresh water.	150	866	2 827 000	2063	148	866	3 710 000	2220
2 sand 187: 4 trap rock 505	Deposited through 5-inch tremie				2307	158			2537
	Immersed about 3 feet below surface of water after depositing in molds.	158			4094+	158			3956
	In damp room 24 hours before immersion.	158			4100	154			4247+
	In damp room 8 weeks before immersion.	158			3457	157			[a] 3389
2 sand 188: 4 trap rock 505	do	159			2716	159			3339
3 sand 187: 6 trap rock 505	Deposited through 5-inch tremie	152			572	151			702
	In damp room 8 weeks before immersion.	159			2225	159			2980
3 sand 187: 6 gravel 502	do	148			2204	149			2311
5 sand 187: 8 rock 505	do	155			1574	153			[b] 1731

[a] At 104 weeks ultimate stress, 2758 pounds per square inch.

[b] At 104 weeks ultimate stress, 1714 pounds per square inch.

TABLE 20

Effect of Different Consistencies on the Compressive Strength of Concrete, Showing Ultimate Stress in Pounds Per Square Inch as Affected by Percentage of Mixing Water

[Each result is the average of tests of three 8 by 16 inch cylinders. Proportion by volume, 1:2:4]

Aggregates		Age when tested, 1 week								Age when tested, 4 weeks		
Limestone and gravel	Sand	5 per cent	6 per cent	7 per cent	8 per cent	9 per cent	10 per cent	11 per cent	12 per cent	6 per cent	7 per cent	8 per cent
Limestone 230	183	1234	1284	1317	1637	1406	1031	779	865	1733	2091	2577
Gravel 39	183	1174	1652	465	613	560	....	....	....	....	....	....

TABLE 21

Effect of Variation in Quantity of Water Used in Mixing Concrete on the Compressive Strength, Showing Ultimate Stress in Pounds Per Square Inch

[Proportion by volume, 1 part cement, 2 parts sand 189, 4 parts stone or gravel 504. Each result is the average of tests of three 8 by 16 inch cylinders]

Consistency [a]	Stone aggregate and age when tested			Gravel aggregate and age when tested		
	7 days	30 days	90 days	7 days	30 days	90 days
Dry, 6 per cent	1435	1835	3939	1448	2370	3616
Quaking, 7 per cent	1515	2579	3535	1162	2180	3001
Mushy, 8 per cent	904	1569	2305	1067	2000	3142
Mushy, 9 per cent	841	1498	2040	894	1715	2620
Fluid, 10 per cent	580	1035	1500	735	1437	2165
Fluid, 11 per cent	....	....	....	490	980	1785

[a] Percentage of water based on total weight of dry materials.

TABLE 22

Modulus of Elasticity and Compressive Strength of Portland Cement Concrete Prepared With Different Quantities of Water

[All results are the average of 3 tests of 8 by 16 inch cylinders or 6-inch cubes, unless otherwise noted. Concrete mixed in the proportion by volume of 1 part cement to 2 parts of sand, 181 to 4 parts of coarse aggregate]

Age in weeks	Property	Granite 175			Gravel 501			Limestone 500			Cinders [a] 507		
		Fluid	Mushy	Quaking	Fluid	Mushy	Quaking	Fluid	Mushy	Quaking	Fluid	Mushy	Quaking
Cylinders:													
4	Percentage of water used	9.0	8.0	6.9	9.6	8.7	7.6	10.9	10.0	8.4	21.7	20.0	19.0
	Modulus of elasticity	3 570 000	4 083 000	4 890 000	3 787 000	3 875 000	4 070 000	3 588 000	3 432 000	4 257 000	1 236 000	1 352 000	1 288 000
	Ultimate stress (lbs. per sq. in.)	2683	3480	4000	2060	2961	3407	3072	2910	2894	1081	1201	1118
13	Percentage of water used	9.0	8.3	7.0	9.8	9.0	8.0	11.0	10.3	8.4	22.1	20.8	19.0
	Modulus of elasticity	4 283 000	4 747 000	4 697 000	4 890 000	5 200 000	5 160 000	4 257 000	3 983 000	3 963 000	2 657 000	2 275 000	1 635 000
	Ultimate stress (lbs. per sq. in.)	3510	([b])	([b])	2954	([b])	([b])	3385	3470	([b])	1764	1819	1726
26	Percentage of water used	9.0	8.4	7.0	9.9	9.0	8.1	11.0	10.0	8.6	22.0	21.2	19.0
	Modulus of elasticity	4 057 000	3 913 000	4 430 000	4 050 000	4 660 000	4 873 000	3 424 000	3 943 000	4 310 000	1 610 000	1 618 000	1 382 000
	Ultimate stress (lbs. per sq. in.)	([b])	([b])	([b])	3846	([b])	([b] [c])	3216	3691	3860	2021	2203	1945
52	Ultimate stress (lbs. per sq. in.)	4908	5299	6278	4823	3938	5442	3900	3720	5109	2457	2308	2091
78	Ultimate stress (lbs. per sq. in.)	5619	6271	6308	....	....	[c] 6567	....	....	....	....	....	....
	Average weight per cubic foot, pounds	147.6	147.6	148.9	139.6	142.4	144.5	146.3	145.6	148.1	115.2	114.9	113.1
Cubes:													
4	Percentage of water used	9.0	8.0	6.9	9.6	8.7	7.6	10.9	10.0	8.4	21.7	20.0	19.0
	Ultimate stress (lbs. per sq. in.)	3156	4089	4518	2999	3547	4612	5141	2975	4367	1256	1191	1378
13	Percentage of water used	9.0	8.3	7.0	9.8	9.0	8.0	11.0	10.3	8.4	22.1	20.8	19.0
	Ultimate stress (lbs. per sq. in.)	4754	4992	5400	....	....	4989	4008	3939	5400+	2015	1855	1861
26	Percentage of water used	9.0	8.4	7.0	9.9	9.0	8.1	11.0	10.0	8.6	22.0	21.2	19.0
	Ultimate stress (lbs. per sq. in.)	4753	4949	5519+	3814	4808	4884	3460	3896	5025	2320	2765	2488
	Average weight per cubic foot, pounds	147.4	147.8	147.7	138.8	142.7	144.8	144.5	145.6	147.8	115.0	113.1	113.5

[a] Proportion of cinder concrete approximately 1 : 2 : 5 by volume. [b] Exceeded capacity of testing machine. Stress exceeded 3900 lbs. per sq. in. [c] Average of 6 tests.

TABLE 23

Relation of "Density" (Solidity Ratio[a]) of the Mixture to the Compressive Strength of Portland Cement Concrete at the Age of 4 Weeks

[All results are the average of tests of three 6-inch cubes. Coarse aggregate limestone 388]

Sand 184					Sand 185				
Proportions by volume (cement: sand: stone)	Per cent mixing water for quaking consistency	"Density"[a]	Weight per cubic foot (pounds)	Ultimate stress (lbs. per sq. in.)	Proportions by volume (cement: sand: stone)	Per cent mixing water for quaking consistency	"Density"[a]	Weight per cubic foot (pounds)	Ultimate stress (lbs. per sq. in.)
1:0:6	8.5	0.818	153.3	2503	1:0½:5½	8.5	0.838	152.9	2249
1:0½:5½	8.5	.841	154.2	2271	1:1:5	9.6	.826	149.8	1985
1:1:5	9.3	.832	154.8	2530	1:2:4	10.8	.789	145.7	1622
1:1½:4½	9.1	.818	153.0	1901	1:3:3	12.7	.745	140.0	1055
1:2:4	9.8	.803	152.3	2018	1:1:8	8.8	.842	152.2	1998
1:3:3	10.3	.771	147.5	1311	1:2:7	9.5	.818	150.7	1594
1:0:9	7.8	.777	134.3	944	1:3:6	11.2	.788	144.7	1053
1:1:8	8.2	.852	149.4	1726	1:4:5	11.8	.751	139.6	685
1:1½:7½	7.9	.844	153.4	1833					
1:2:7	8.5	.835	152.3	1471					
1:3:6	9.1	.806	150.7	1195					
1:4:5	9.7	.780	148.2	885					

[a] See text, p. 12.

TABLE 24

Relation of the "Density" (Solidity Ratio[a]) of the Mixture to the Compressive Strength of Portland Cement Concrete at the Age of 4 Weeks

[Each result is the average of tests of three 6-inch cubes]

Aggregate	Proportions by volume (cement: sand: stone)	Per cent mixing water for mushy consistency	"Density"[a] (solidity ratio)	Yield[b]	Weight per cubic foot (pounds)	Ultimate stress (lbs. per sq. in.)
Stone 147 with fine material from crusher run	1:0:9	8.6	0.757	0.915	136	1338
	1:1:8	9.9	.818	.950	149	1890
	1:2:7	8.2	.823	1.073	145	2037
	1:3:6	9.1	.814	1.280	148	2051
	1:4:5	9.5	.789	1.554	150	1506
	1:2:4	9.4	.806	1.292	148	2692
Gravel 513 with sand 190	1:0:6	7.4	.834	.841	137.0	1687
	1:0½:5½	7.8	.891	.873	146.9	1780
	1:1:5	8.1	.915	.931	151.6	2478
	1:2:4	9.1	.895	1.180	149.7	2430
	1:3:3	11.2	.861	1.622	145.0	1874
	1:0:9	6.6	.795	.861	130.2	758
	1:1:8	7.2	.883	.874	145.3	1412
	1:2:7	7.8	.924	.945	150.8	1602
	1:3:6	8.6	.893	1.135	148.0	1478
	1:4:5	10.5	.858	1.409	141.3	982

[a] See text, p. 12.

[b] Resulting volume of concrete calculated on basis of volume of stone used at 1.000.

TABLE 25

Relation of the "Density"[a] (Solidity Ratio) of the Mixture to the Compressive Strength of Portland Cement Concrete at the Age of 4 Weeks

[Each result is the average of tests of three 6-inch cubes]

Proportions by volume (cement : sand : gravel)	Gravel 514 : sand 181		Gravel 514 : sand 198		Gravel 516 : sand 181		Gravel 516 : sand 199	
	"Density"[a] (solidity ratio)	Ultimate stress (lbs. per sq. in.)	"Density"[a] (solidity ratio)	Ultimate stress (lbs. per sq. in.)	"Density"[a] (solidity ratio)	Ultimate stress (lbs. per sq. in.)	"Density"[a] (solidity ratio)	Ultimate stress (lbs. per sq. in.)
1:0:9	0.759	774			0.762	869		
1:1:8	.763	1353	0.806	1226	.808	1085	0.769	799
1:1½:7½	.808	1697	.860	2663	.830	2335	.830	1902
1:2:7	.856	2491	.849	2247	.869	2556	.864	2031
1:2½:6½	.845	1736	.847	1873	.848	2376	.874	2260
1:3:6	.840	2053	.837	1940	.815	2240	.857	2180
1:4:5	.798	1237	.789	809	.808	1590		
1:0:6	.780	1408			.764	1487		
1:0½:5½	.817	1773	.800	1343	.828	2543	.829	2116
1:1:5	.852	3035	.851	3634	.861	3457	.862	2693
1:1½:4½	.849	3076	.844	2776	.868	4101	.860	3345
1:2:4	.822	3175	.832	3104	.836	2974	.854	3376
1:3:3	.788	2011	.782	1907	.789	2206		
1:4:2	.736	1309	.738	1119	.742	1500		

[a] See text, p. 12.

TABLE 26

Compressive Strength, Modulus of Elasticity, Yield Point, and Density of Concretes Prepared with 3 Fine Aggregates and 3 Coarse Aggregates

[Each result is the average of tests of two or more 8 by 16 inch cylinders. Stored in air under cover. Sprinkled twice daily for the first 30 days]

Series	Proportions by volume (cement: sand : stone)	Aggregates		Per cent of water required for quaking consistency	"Density" [a] (solidity ratio)	Ultimate stress (lbs. per sq. in.)		Modulus of elasticity, 90 days	Yield point (lbs. per sq. in.), 90 days
		Fine	Coarse			30 days	90 days		
2	1:1:5	Sand 194	Trap rock 525	9.0	0.775	1660	2342	2 060 000	870
	1:2:4			9.9	.777	1840	2740	2 665 000	1220
	1:3:3			12.7	.712	953	1952	1 917 500	860
	1:2:7			9.0	.813	1210	1792	2 010 000	590
	1:3:6			9.9	.775	965	1712	1 950 000	655
	1:4:5			12.4	.722	626	1195	1 362 500	480
3	1:1:5	Sand 195	do	8.5	(b)	1140	1810	1 701 000	640
	1:2:4			9.0	(b)	1765	2830	2 695 000	1215
	1:3:3			10.0	(b)	1745	2510	2 530 000	1055
	1:2:7			8.0	(b)	1272	1853	1 841 000	570
	1:3:6			8.0	(b)	1220	1972	2 380 000	700
	1:4:5			9.7	(b)	870	1502	2 075 000	515
4	1:1:5	Trap-rock screenings 429	do	9.0	.759	1766	2540	1 680 000	900
	1:2:4			11.5	.780	2298	3430	3 015 000	1530
	1:3:3			13.0	.759	1597	2183	2 097 500	680
	1:2:7			9.2	.754	1336	2120	1 747 500	695
	1:3:6			10.9	.736	1035	1655	1 825 000	367
	1:4:5			12.7	.715	855	1325	1 370 000	400

[a] See text, p. 12.

[b] Insufficient material for density tests.

TABLE 26—Continued

Compressive Strength, Modulus of Elasticity, Yield Point, and Density of Concretes Prepared with 3 Fine Aggregates and 3 Coarse Aggregates—Continued

Series	Proportions by volume (cement: sand : stone)	Aggregates: Fine	Aggregates: Coarse	Per cent of water required for quaking consistency	"Density" (solidity ratio)	Ultimate stress (lbs. per sq. in.): 30 days	Ultimate stress (lbs. per sq. in.): 90 days	Modulus of elasticity, 90 days	Yield point (lbs. per sq. in.) 90 days
5	1:0:4½			9.5	.805	1837	2350	2 280 000	900
	1:0:6			8.9	.813	1295	1771	2 092 500	765
	1:1:5			9.2	.778	1340	1875	1 990 000	685
	1:2:4			10.6	.752	1087	1469	1 960 000	550
	1:3:3	Sand 194	Bank-run gravel 527	12.9	.711	860	1268	1 328 000	428
	1:0:9			7.9	.801	762	1151	1 771 000	465
	1:2:7			9.1	.760	615	814	1 357 000	233
	1:3:6			10.6	.734	528	632	1 022 000	140
	1:4:5			12.4	.705	365	595	1 080 000	152
6	1:1:5			8.9	.785	1412	1850	2 375 000	680
	1:2:4			9.5	.777	1421	1910	2 150 000	760
	1:3:3	Sand 195	do	9.9	.755	1351	1745	1 692 000	620
	1:2:7			8.1	.820	816	965	1 444 000	398
	1:3:6			8.8	.794	731	862	1 340 000	337
	1:4:5			10.6	.750	632	815	1 150 000	230
7	1:1:5			9.0	(a)	1625	2216	2 862 000	727
	1:2:4			9.6	(a)	1240	1642	1 810 000	563
	1:3:3	Trap-rock screenings 429	Gravel 526	10.9	(a)	1289	1732	1 560 000	450
	1:2:7			9.1	(a)	685	786	1 152 000	310
	1:3:6			10.3	(a)	536	611	808 000	205
	1:4:5			12.1	(a)	833	1060	1 265 000	320

8	1:1:5	Sand 194	do	7.5	.827	1435	2355	2 725 000	720
	1:2:4			9.2	.794	1600	2500	2 840 000	960
	1:3:3			11.75	.773	1250	1735	1 961 000	577
	1:2:7			7.1	.828	1195	1730	2 351 000	685
	1:3:6			8.9	.789	896	1441	2 250 000	525
	1:4:5			11.2	.758	680	1018	1 787 000	287
9	1:1:5	Sand 195	do	7.7	.771	1385	1875	2 395 000	840
	1:2:4			8.5	.816	1825	2638	3 136 000	1165
	1:3:3			9.0	.785	1692	2420	2 519 000	833
	1:2:7			7.25	.824	1177	1625	2 105 000	605
	1:3:6			8.0	.822	985	1215	1 695 000	490
	1:4:5			10.4	.793	1032	1409	2 135 000	510
10	1:1:5	Trap-rock screenings 429	do	7.1	.796	1465	1922	2 380 000	925
	1:2:4			9.1	.808	1507	1923	2 027 000	775
	1:3:3			9.9	.779	1422	1751	1 842 000	585
	1:2:7			8.0	.804	1196	1398	1 449 000	220
	1:3:6			8.1	.816	960	1069	1 214 000	210
	1:4:5			10.8	.819	831	890	1 245 000	262

[a] Insufficient material for density tests.

TABLE 27

Effect of Size of Aggregate on the Compressive Strength

[Each result is the average of tests of two 14-inch cubes. Stored in air under cover; sprinkled twice daily; age 30 days]

Proportions by volume and composition of concrete; 1 part cement to—	Ultimate stress (lbs. per sq. in.)	Proportions by volume and composition of concrete; 1 part cement to—	Ultimate stress (lbs. per sq. in.)
1 part sand 195, 5 parts of mixture of 10 per cent screenings 429, 50 per cent trap rock 524, and 40 per cent trap rock 525	3570	2 parts screenings 429, 4 parts screened gravel 527	[a] 1682
2 parts sand 195, 4 parts same mixture as above	2590	2 parts screenings 429, 4 parts screened gravel 527, 1 part trap rock 524	[a] 2466
3 parts sand 195, 3 parts same mixture as above	1955	2 parts screenings 429, 4 parts screened gravel 527, 2 parts trap rock 524	[a] 2120
2 parts sand 195, 7 parts same mixture as above	1975	2 parts screenings 429, 4 parts screened gravel 527, 3 parts trap rock 524	[a] 2015
3 parts sand 195, 6 parts same mixture as above	1619	2 parts screenings 429, 4 parts screened gravel 527, 4 parts trap rock 524	[a] 1890

[a] Result of 1 test.

TABLE 28

Compressive Strength of Portland Cement Concretes Exposed to Different Conditions During the Early Hardening Period

[All results are the average of 3 tests of 8 by 16 inch cylinders]

Series: [a]	Proportions by volume (cement: sand 189) gravel 504	Cement used—shipment No. —	Age when tested, 1 week: Per cent water, mushy consistency	Age when tested, 1 week: Weight per cubic foot (pounds)	Age when tested, 1 week: Range of 3 tests (pounds)	Age when tested, 1 week: Ultimate stress (lbs. per sq. in.)	Age when tested, 4 weeks: Per cent water, mushy consistency	Age when tested, 4 weeks: Weight per cubic foot (pounds)	Age when tested, 4 weeks: Range of 3 tests (pounds)	Age when tested, 4 weeks: Ultimate stress (lbs. per sq. in.)	Age when tested, 12 weeks: Per cent water, mushy consistency	Age when tested, 12 weeks: Weight per cubic foot (pounds)	Age when tested, 12 weeks: Range of 3 tests (pounds)	Age when tested, 12 weeks: Ultimate stress (lbs. per sq. in.)
1	1 : 1½ : 3	1	10.0	142	69	1010	10.0	142	47	1842	10.0	140	50	2207
		2	10.0	144	105	728	10.0	142	60	1844	10.0	142	305	2289
		3	10.0	144	82	848	10.0	142	223	1691	10.0	140	30	2130
2	1 : 2 : 4	1	9.0	142	2	565	9.0	144	146	1152	9.0	142	112	1488
		2	9.0	144	39	468	9.0	142	133	1176	9.0	140	131	1469
		3	9.0	142	64	411	9.0	140	83	983	9.0	138	152	1450
3	1 : 2½ : 5	1	8.5	144	28	555	8.5	142	153	1150	8.5	140	100	1450
		2	8.5	144	46	418	8.5	140	111	1083	8.5	140	12	1375
		3	8.5	140	61	555	8.5	142	140	1259	8.5	142	71	1564
[b] 4	1 : 2 : 4	[b] 1	9.0	....	....	....	9.0	146	500	1834	9.0	144	517	[b] 2500

[a] Series 1, 2, and 3 were sprinkled daily for one week and then stored indoors in a relatively dry atmosphere. Series 4 was stored in a damp room for 4 weeks and then placed in the open exposed to the weather.

[b] Subsequent tests gave the following results: 6 months=2353; 9 months=2705; 12 months=2926; 18 months=2802.

TABLE 29

Compressive Strength of Portland Cement Concretes Exposed to Different Conditions During the Early Hardening Period; concrete Mixed in the Proportion by Volume of 1 Part Cement to 2 Parts of Sand 183 to 4 Parts of Gravel 501; Quaking Consistency 8.2 Per Cent of Water

[Each result is the average of 12 tests of 8 by 16 inch cylinders at the age of 4 weeks]

Method of storage	Weight per cubic foot (pounds)	Yield point, per cent ultimate stress	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)	Range of 12 tests (pounds)
In damp closet	143.6	53	3 915 000	2612	800
In open air, exposed to weather	141.7	50	3 440 000	2085	1026

TABLE 30

Effect of Steam Under Pressure on the Compressive Strength of Portland Cement Mortar, Mixed to a Plastic Consistency With 9 Per Cent of Water in the Proportion by Volume of 1 Part Cement to 4 Parts of Sand 181

[All results are the average of three tests of 8 by 16 inch cylinders]

Gauge pressure (lbs. per sq. in.)	Temperature (°F.)	Duration of exposure to steam (hours)	Age when tested, 2 days				Age when tested, 7 days				Age when tested, 14 days				Age when tested, 28 days	
			Weight per cubic foot (lbs.)	Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)	Weight per cubic foot (lbs.)	Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)	Weight per cubic foot (lbs.)	Yield point (lbs. per cu. ft.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)	Weight per cubic foot (lbs.)	Ultimate stress (lbs. per sq. in.)
Not steamed			133			613				1296				1528	134	1727
0	212	48				1267										
2	218	24	131	800	1 900 000	1808	132	800	2 040 000	1792	133	1300	2 160 000	[a] 1805		
10	239	24	130	700	1 460 000	1786	132	1000	1 450 000	1555	132	300	2 670 000	1701	133	1902
20	258	24	132	1100	2 000 000	2139	134	1100	2 100 000	2284			2 740 000	[b] 2740		
40	286	24	130	800	2 900 000	3292	134	700	3 660 000	3381	134			3984		
80	323	24	130	1500	2 840 000	[c] 3964	135	1200	3 500 000	[d] 3966				[e] 4433		
80	323	24	130			4487	133			4187						

[a] At 113 days ultimate stress (lbs. per sq. in.)=3364.
[b] At 247 days ultimate stress (lbs. per sq. in.)=3940.
[c] Two specimens tested at age of 15 days. Average stress 4590.
[d] Broken at 15 days. Average stress 4840.
[e] At 77 days ultimate stress (lbs. per sq. in.)=5054.

TABLE 31

The Relative Compressive Strength of Concretes Made of Various Coarse Aggregates Combined with the Same Fine Aggregate, Sand 183

[Each result is the average of three or more tests at the age of 4 weeks]

Coarse aggregate	Proportions, by volume (cement: sand: stone), showing ultimate strength in pounds per square inch	
	1:2:4	1:3:6
Crusher run limestones:		
251	2555	1466
307	2243	1057
150	3184	1301
210	1638	1350
Bank-run gravels:		
37	1570	1029
35	3175	2053
24	2520	1925
39	2175	1917
36	2974	2240
28	927	425

TABLE 31a

Compressive Strength of Portland Cement Concretes Composed of One Coarse Aggregate with Two Different Sands

[Each result is the average of two tests of 8 by 16 inch cylinders]

Proportions (by volume) 1 part cement to—	Per cent water	"Density"	Compressive strength (lbs. per sq. in.)	
			9 days	30 days
2 parts sand 200 : 4 parts stone 508	7.6	0.832	1950	2765
2 parts sand 201 : 4 parts stone 508	7.6	.823	1687	2925

TABLE 31b

Compressive Strength of Concrete Containing Chats (Zinc Mine Tailings)

[Results average of two tests at quaking consistency]

Proportions by volume	Per cent mixing water	Ultimate compressive stress (lbs. per sq. in.)		
		7 days	30 days	90 days
1 part cement : 4 parts chats 430	10.5	....	[a] 3100	....
1 part cement : 6 parts chats 430	10.0	....	[a] 1805	....
Cement : sand 431 : chats 430:				
1 : 1 : 5	12.5	....	1750	....
1 : 1½ : 3	13.1	981	1755	2120
1 : 2 : 4	12.0	750	1526	1812
1 : 2½ : 5	12.0	488	851	1030
Cement : chats 430 : crushed rock: 1 : 2 : 4	10.0	....	[b] 2270	....

[a] Insufficient fine material. Surfaces honeycombed.
[b] Chats used as a fine aggregate. Surfaces of cylinders honeycombed, showing lack of fine material.

TABLE 31c

Compressive Strength of Concrete Containing Chats (Zinc Mine Tailings)

[Results average of two tests at quaking consistency]

Proportions by volume	Per cent mixing water	Ultimate compressive stress (lbs. per sq. in.)		
		7 days	30 days	90 days
Cement : chats 432:				
1 : 3	16.0	....	a 3680	....
1 : 4	12.5	....	a 2855	....
Cement : chats 434 : chats 432: 1 : 1 : 5	12.5	....	1560	....
Cement : chats 434 : chats 433:				
1 : 1½ : 3	10.5	1682	3042	3220
1 : 2 : 3	9.2	1372	1522	1722
1 : 2½ : 5	9.0	596	1025	925
Cement : chats 432 : crushed stone: 1 : 2 : 4	10.5	....	b 1920	....

a Insufficient fine material. Surfaces honeycombed.

b Run-of-mine chats used as a fine aggregate. Surfaces of cylinders honeycombed, showing lack of fine material.

TABLE 32

Compressive Strength of Portland Cement Concretes Prepared with One Aggregate Which Was Regraded

[Each result is the average of tests of three 8 by 16 inch cylinders at the age of 8 weeks]

Size of material	Proportions by volume	Per cent water for mushy consistency	"Density"[a]	Weight per cubic foot (pounds)	Ultimate stress (lbs. per sq. in.)
Pit-run gravel 55	1:0:6	10.6	0.85	149	2071
Coarse gravel 55, above ¼ inch	1:1:5	9.3	.86	152	1996
Fine gravel 55, below ¼ inch	1:2:4	9.6	.85	150	1815
	1:3:3	11.4	.82	146	1555
Coarse gravel 55, above No. 6 sieve	1:1:5	9.5	.84	151	2194
Fine gravel 55, below No. 6 sieve	1:2:4	10.6	.83	150	1534
	1:3:3	11.6	.80	145	1694

[a] See text, p. 12.

TABLE 33

Relative Compressive Strength of Portland Cement Concretes Containing Various Percentages of Cement, the Ratio of Fine to Coarse Aggregate Remaining the Same

[Each result is the average of tests of three 8 by 16 inch cylinders at the age of 4 weeks]

Proportion by volume (cement : sand : stone)	Gravel 54 and sand 183					Limestone 451 and sand 183				
	Per cent of water for mushy consistency	Weight per cubic foot (pounds)	Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)	Per cent of water for mushy consistency	Weight per cubic foot. (pounds)	Yield point (lbs. per sq. ft.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)
1 : 1 : 2	10.3	147	2700	4 839 000	4765	9.6	151	2433	4 771 000	4889
1 : 1½ : 3	9.7	145	1800	4 329 000	4009	9.6	151	2400	4 500 000	4227
1 : 2 : 4	8.9	144	1754	4 225 000	3308	9.2	147	1417	2 777 000	2875
1 : 2½ : 5	10.0	143	1050	3 834 000	2293					
1 : 3 : 6	9.9	142	825	3 450 000	1809					
1 : 4 : 8	9.3	140	300	3 734 000	1203					

TABLE 34

Compressive Strength of Portland Cement Concretes Prepared With a Number of Different Aggregates Mixed in Various Proportions

[Each result is the average of tests of three 8 by 16 inch cylinders unless otherwise noted]

Aggregates		Proportions by volume (cement : sand : stone)	Age when tested, 4 weeks						Age when tested, 13 weeks					
Coarse	Fine		Percentage mixing water	Weight per cubic foot (pounds)	Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)	Range of 3 tests (pounds)	Percentage mixing water	Weight per cubic foot (pounds)	Yield point (lbs. per sq. in.)	Modulus of elasticity	Ultimate stress (lbs. per sq. in.)	Range of 3 tests (pounds)
Limestone 221	Sand 183	1 : 2 : 4 [a]	10.6		870	3 440 000	2241	1090	10.6		1100	3 870 000	2904	1290
		1 : 3 : 6 [a]	10.9		410	2 820 000	1222	416	10.9		690	3 340 000	1804	652
Limestone 206	do	1 : 1½ : 3 [b]	12.2				2358	666					3116	785
		1 : 3 : 6 [b]	12.0				1114	145					1483	260
		1 : 4 : 8 [b]	12.6				725	25					985	297
Granite 449	do	1 : 2 : 4	7.9	148			2549							
		1 : 3 : 6	7.5	147			2071							
Do	Screenings 427.	1 : 1 : 5	7.1	145			2404							
Gravel 39	Sand 183	1 : 2 : 4	8.7	147			2345							
		1 : 3 : 3	9.9	143			2344							
		1 : 2 : 7	7.0	145			1748							
		1 : 3 : 6	8.2	144			1528							
		1 : 4 : 5	9.0	144			1447							
		1 : ¾ : 3¾	9.1	144			3075	460	9.2	145	1700	4 653 000	3740	530
		1 : 1 : 5	8.9	143			2007	480	9.3	144	633	3 970 000	2393	210
		1 : 2 : 4 [a]	9.6		1200	4 390 000	2619	1130	9.6		1790	4 840 000	3496	1553
Gravel 514	Sand 181	1 : 1½ : 3 [b]	9.4				3667	1003	9.4				c 4000+	
		1 : 1½ : 7½	8.4	143			1041	59	9.0	138	400	3 433 000	1346	190
		1 : 3 : 6 [b]	9.5				1395	379	9.5				2004	729
		1 : 3 : 6 [a]	9.8		480	3 250 000	1168	783	9.8		840	4 130 000	1810	1187
Gravel 516	do	1 : 4 : 8	10.4				719	196	10.4				1095	524

		1 : 1 : 5					3666							
		1 : 2 : 4					2866							
Gravel 514	Sand 198	1 : 2 : 7					1972							
		1 : 3 : 6					1545							
		1 : 1½ : 4½					3559							
Gravel 516	Sand 199	1 : 2 : 4					3347							
		1 : 3 : 6					1568							
		1 : 1 : 5					2646							
		1 : 1½ : 7½					1106							
		1 : 3 : 6					2134							
		1 : 1 : 5					3315							
		1 : 2 : 7					2443							
		1 : 2½ : 6½					1684							
		1 : 3 : 6					2235							

[a] Average of 27 tests. [b] Average of 9 tests. [c] Exceeded the capacity of the testing machine.

TABLE 35

Variation in Weight Per Cubic Foot of Concrete With Variation in Consistency, Percentage of Cement, and "Density"[a]

Proportions by volume	Weight per cubic foot of gravel 54 and sand 183, mushy consistency	Proportions by volume, 1:2:4, coarse aggregate	Weight per cubic foot			Proportions by volume	Stone 388 and sand 184		Stone 388 and sand 185	
			Fluid consistency	Mushy consistency	Quaking consistency		Weight per cubic foot	"Density"[a]	Weight per cubic foot	"Density"[a]
1:1:2	147	Cinder 507	115.2	114.9	113.1	1:0:6	153	0.818	....	....
1:1½:3	145	Granite 175	147.6	147.7	148.9	1:0½:5½	154	.841	153	0.838
1:2:4	144	Gravel 501	139.6	142.7	144.5	1:1:5	155	.832	150	.826
1:2½:5	143	Limestone 500	144.7	145.9	147.8	1:1½:4½	153	.818	....	....
1:3:6	142					1:2:4	154	.803	146	.789
1:4:8	140					1:3:3	147	.771	140	.745
						1:0:9	134	.777	....	....
						1:1:8	149	.852	152	.842
						1:1½:7½	152	.854	....	....
						1:2:7	152	.835	151	.818
						1:2½:6½	....	....	150	....
						1:3:6	151	.806	145	.788
						1:4:5	148	.780	140	.751

[a] See text, p. 12.

TABLE 36

Compressive Strength of Portland Cement Concretes at the Age of 2, 7, and 14 Days. Concrete Mixed in the Proportion of 1 Part Cement to 2 Parts Sand 183 to 4 Parts of Coarse Aggregate

[Each result is the average of tests of nine 8 by 16 inch cylinders]

	Cinder 507. Age when tested			Gravel 39. Age when tested			Limestone 220. Age when tested			Granite 317. Age when tested		
	2 days	7 days	14 days	2 days	7 days	14 days	2 days	7 days	14 days	2 days	7 days	14 days
Yield point, pounds per square inch	67	140	260	140	470	700	100	410	540	250	470	500
Modulus of elasticity	700 000	1 210 000	1 420 000	2 110 000	3 500 000	4 310 000	1 330 000	2 530 000	2 870 000	1 980 000	3 080 000	3 640 000
Ultimate stress, pounds per square inch	308	758	1119	426	1440	2048	370	1313	1534	737	1627	2057
Range of 9 tests, pounds	75	147	380	443	253	754	276	567	992	200	557	451
Percentage of water for quaking consistency	....	15.7–16.0	....	....	9.6	....	....	10.1–12.0	....	....	8.3	....

TABLE 37

Compressive Strength of Portland Cement Concrete Composed of 1 Part, by Volume, Cement to 2 Parts of Sands 182, 196, and 183 and 4 Parts of Limestone 199 Mixed to a Mushy Consistency With 12.6 to 14.1 Per Cent of Water

[Each result is the average of tests of twenty-four 8 by 16 inch cylinders or 6-inch cubes]

	Age when tested, 4 weeks		Age when tested, 13 weeks		Age when tested, 26 weeks		Age when tested, 52 weeks	
	Cylinders	Cubes	Cylinders	Cubes	Cylinders	Cubes	Cylinders	Cubes
Ultimate stress, pounds per square inch	1764	2089	2366	2914	2573	2993	2723	....
Range, pounds per square inch	642	1031	516	817	568	[a]797	753	....

[a] Average of 15 tests.

TABLE 38

Compressive Strength of Portland Cement Concretes Composed of 1 Part, by Volume, Cement to 6 Parts and 9 Parts, Respectively, of Bank Run Gravel 53

[Each result is the average of tests of three 8 by 16 inch cylinders]

Proportion by volume	Per cent water for mushy consistency	"Density" [a]	Age when tested, 4 weeks		Age when tested, 13 weeks		Age when tested, 26 weeks		Age when tested, 52 weeks	
			Weight per cubic foot (pounds)	Ultimate stress (lbs. per sq. in.)	Weight per cubic foot (pounds)	Ultimate stress (lbs. per sq. in.)	Weight per cubic foot (pounds)	Ultimate stress (lbs. per sq. in.)	Weight per cubic foot (pounds)	Ultimate stress (lbs. per sq. in.)
1:6	11.1	0.879	141	1082	142	1362	142	1487	142	2050
1:9	13.0	.883	141	478	141	670	140	941	136	1207

[a] See text, p. 12.

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